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(12) **United States Patent**
Bone

(10) **Patent No.: US 10,509,201 B2**
(45) **Date of Patent: Dec. 17, 2019**

(54) **NEAR-INFRARED LENS FOR CAMERAS IN MOBILE DEVICES**

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(72) Inventor: **Matthew Bone**, Fremont, CA (US)

(73) Assignee: **Genius Electronic Optical Co., Ltd.**, Taichung (TW)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **16/275,745**

(22) Filed: **Feb. 14, 2019**

(65) **Prior Publication Data**

US 2019/0258029 A1 Aug. 22, 2019

Related U.S. Application Data

(60) Continuation of application No. 15/829,330, filed on Dec. 1, 2017, now abandoned, which is a division of application No. 14/746,772, filed on Jun. 22, 2015, now Pat. No. 9,864,168.

(60) Provisional application No. 62/015,867, filed on Jun. 23, 2014, provisional application No. 62/052,181, filed on Sep. 18, 2014, provisional application No. 62/061,516, filed on Oct. 8, 2014.

(51) **Int. Cl.**

G02B 9/34	(2006.01)
G02B 13/00	(2006.01)
G02B 13/14	(2006.01)

(52) **U.S. Cl.**
CPC ***G02B 13/004*** (2013.01); ***G02B 9/34*** (2013.01); ***G02B 13/0035*** (2013.01); ***G02B 13/14*** (2013.01)

(58) **Field of Classification Search**
CPC G02B 13/004; G02B 9/34
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2014/0078581 A1* 3/2014 Tsai G02B 13/14 359/357

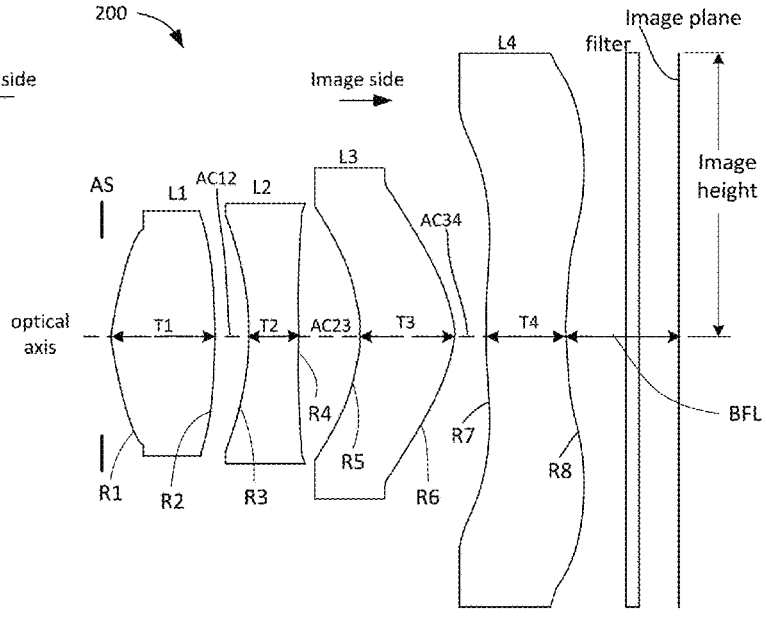
* cited by examiner

Primary Examiner — Joseph P Martinez
(74) *Attorney, Agent, or Firm* — Kilpatrick Townsend & Stockton LLP

(57) **ABSTRACT**

An optical imaging system includes, in the given order from the object side to the image side, a first lens element, a second lens element, a third lens element, and a fourth lens element arranged along an optical axis. The lens elements of the optical imaging systems may be made of the same material having absorption in visible wavelengths and high transmission in near infrared radiation. The lens elements may be coated with an antireflective coating that is optimized for near infrared radiation. The optical imaging system satisfies the relations $2.13° \leq HFOV/Fno \leq 8.75°$, and $0.56 \leq G23/T1 \leq 1.54$, where HFOV is the half field of view and Fno is the F number of the optical imaging system, G**23** is an air gap between the second and third lens elements along the optical axis, and T**1** is a thickness of the first lens element along the optical axis.

20 Claims, 30 Drawing Sheets



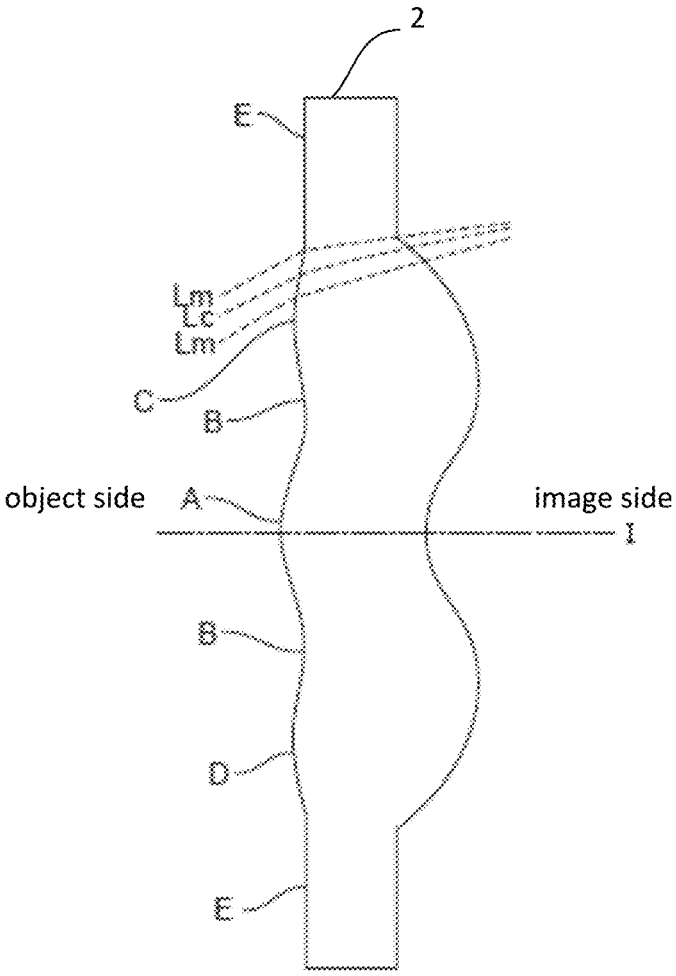


Figure 1

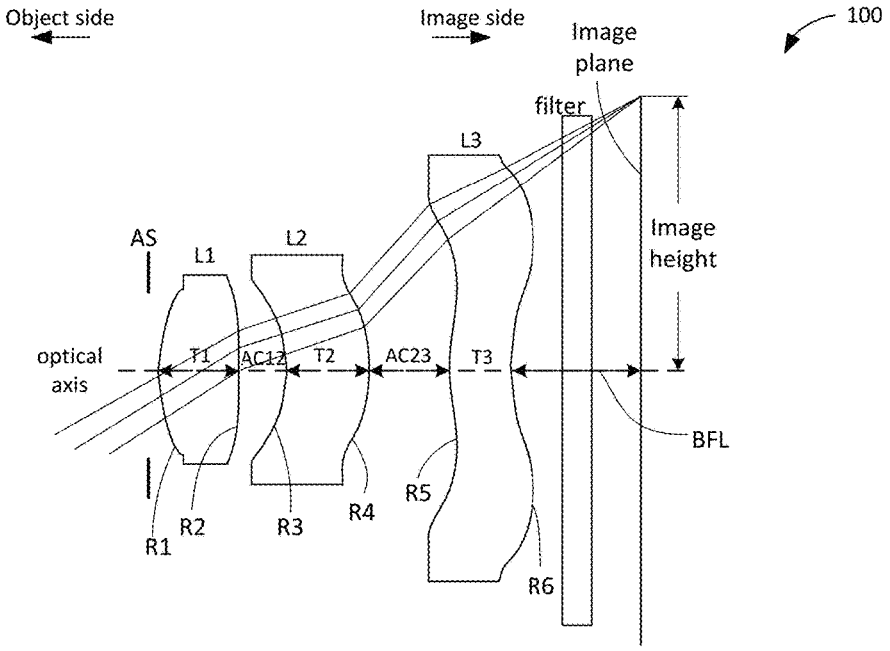


Figure 2A

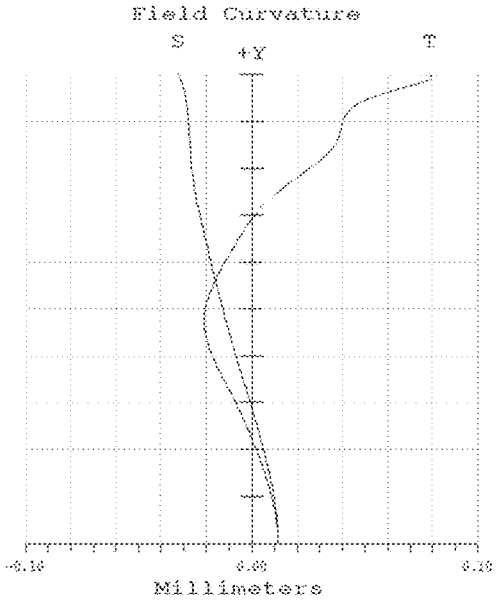


Figure 2B

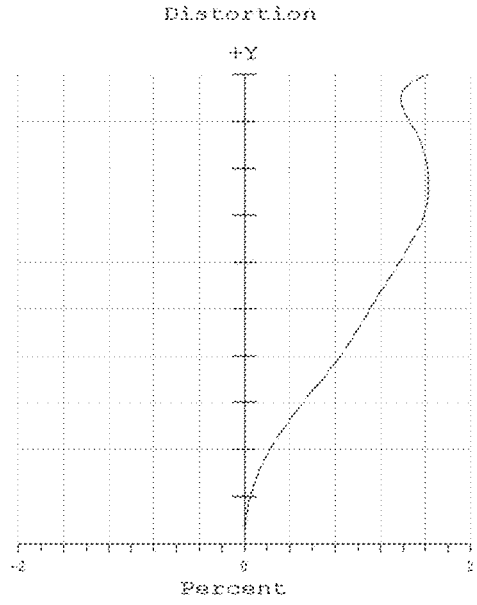


Figure 2C

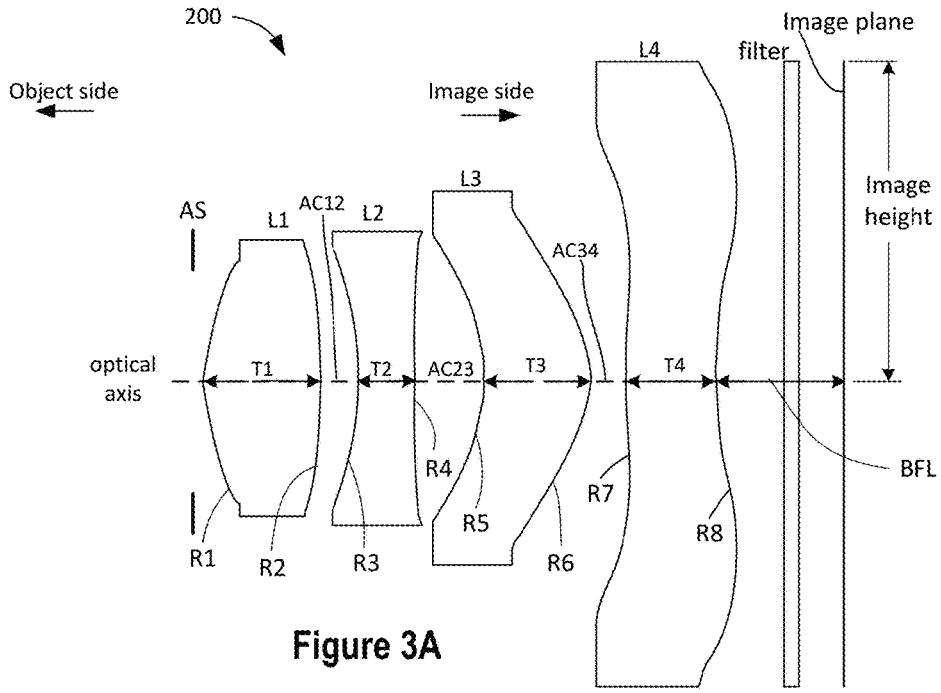


Figure 3A

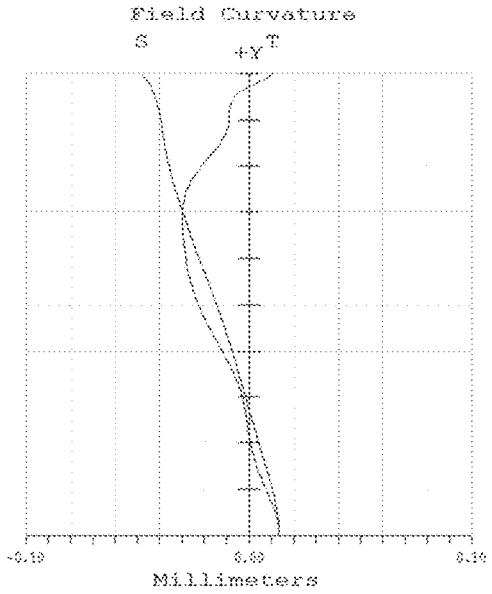


Figure 3B

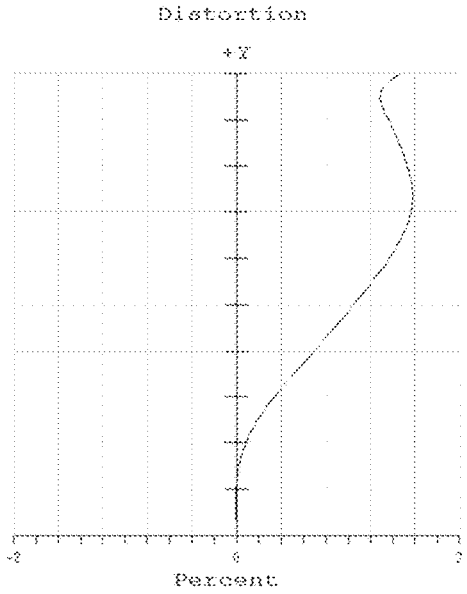
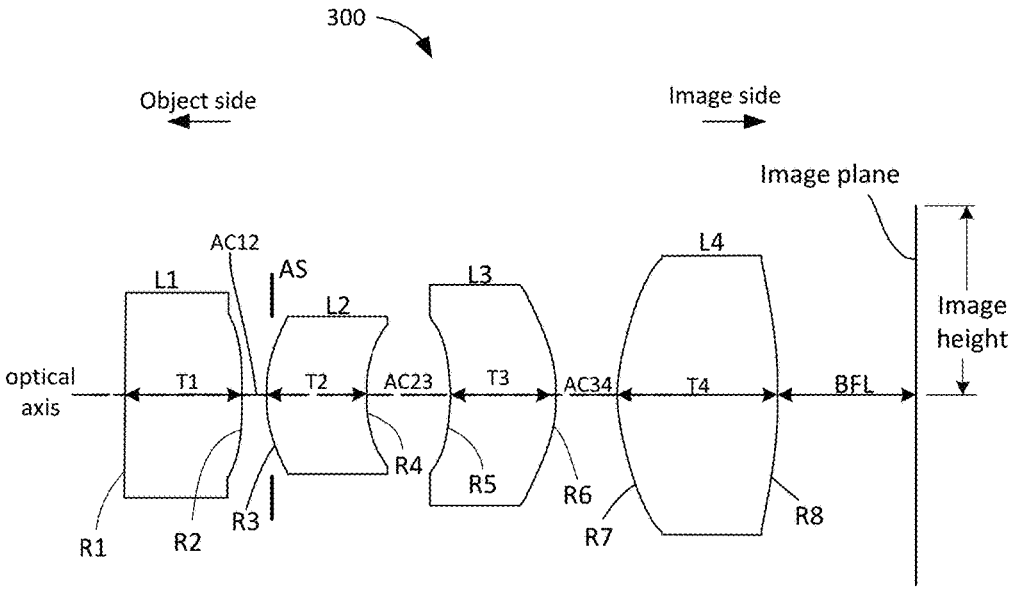


Figure 3C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Object side
Image side
Image plane
AC12
AS
L1
L2
L3
L4
Image height
optical axis
T1
T2
AC23
T3
AC34
T4
BFL
R1
R2
R3
R4
R5
R6
R7
R8

Figure 4

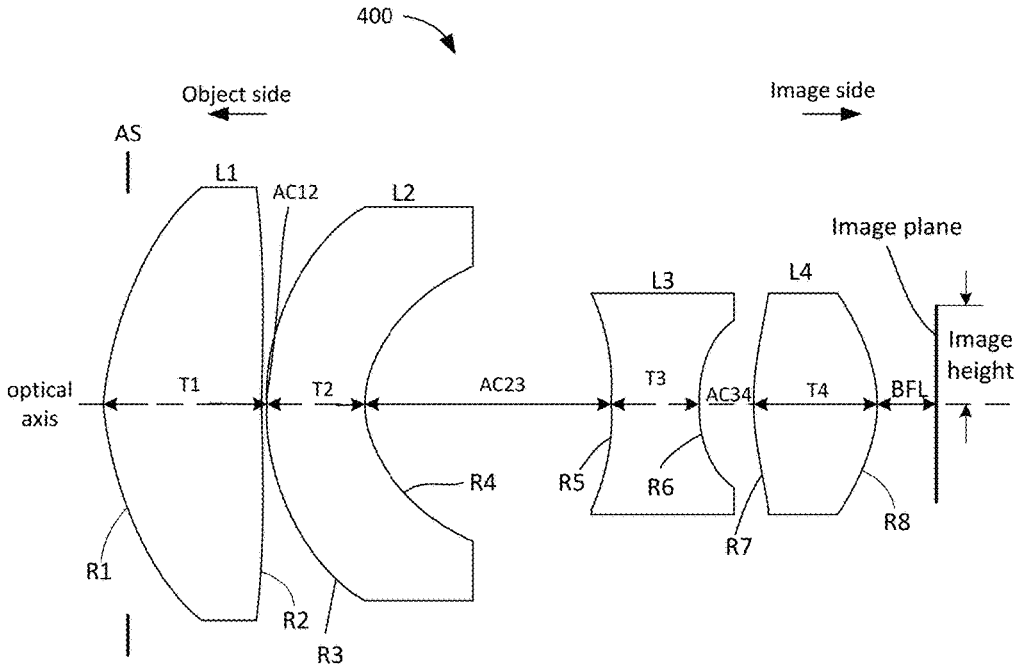


Figure 5A

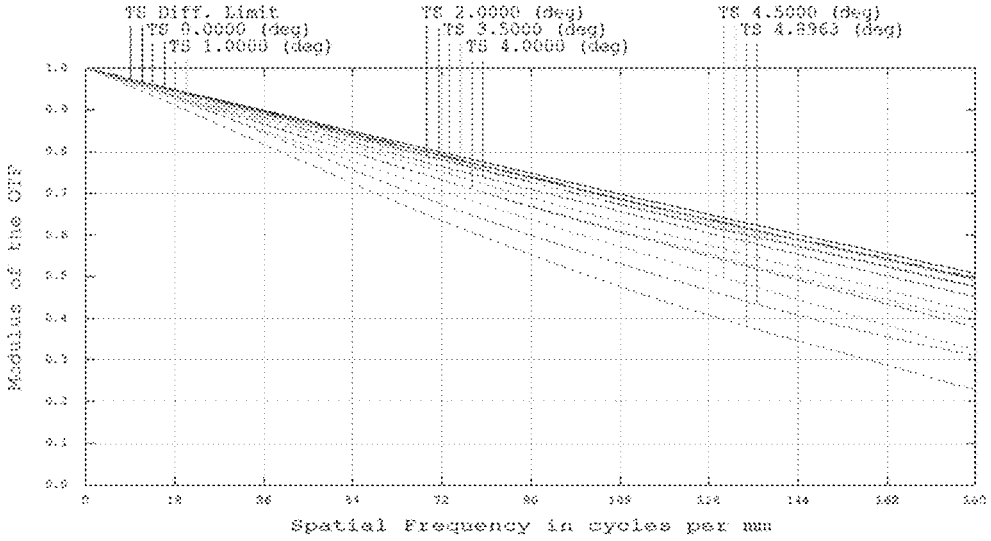
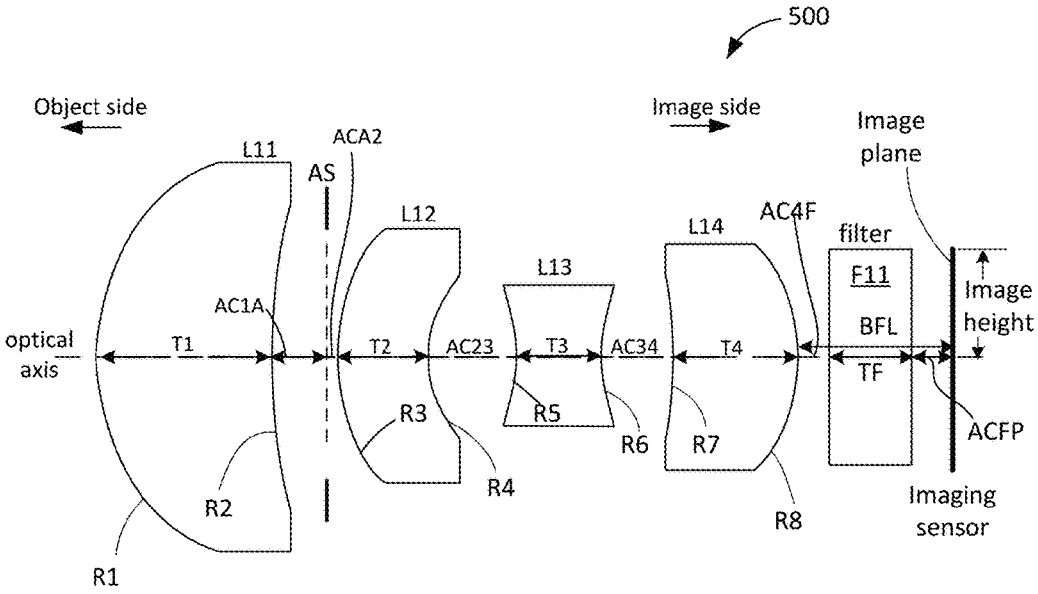


Figure 5B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Object side
Image side
Image plane
L11
ACA2
AS
L12
L13
L14
AC4F
filter
F11
Image height
AC1A
optical axis
T1
T2
AC23
T3
AC34
T4
BFL
TF
R3
R5
R6
R7
ACFP
R2
R4
R8
Imaging sensor
R1

Figure 6A

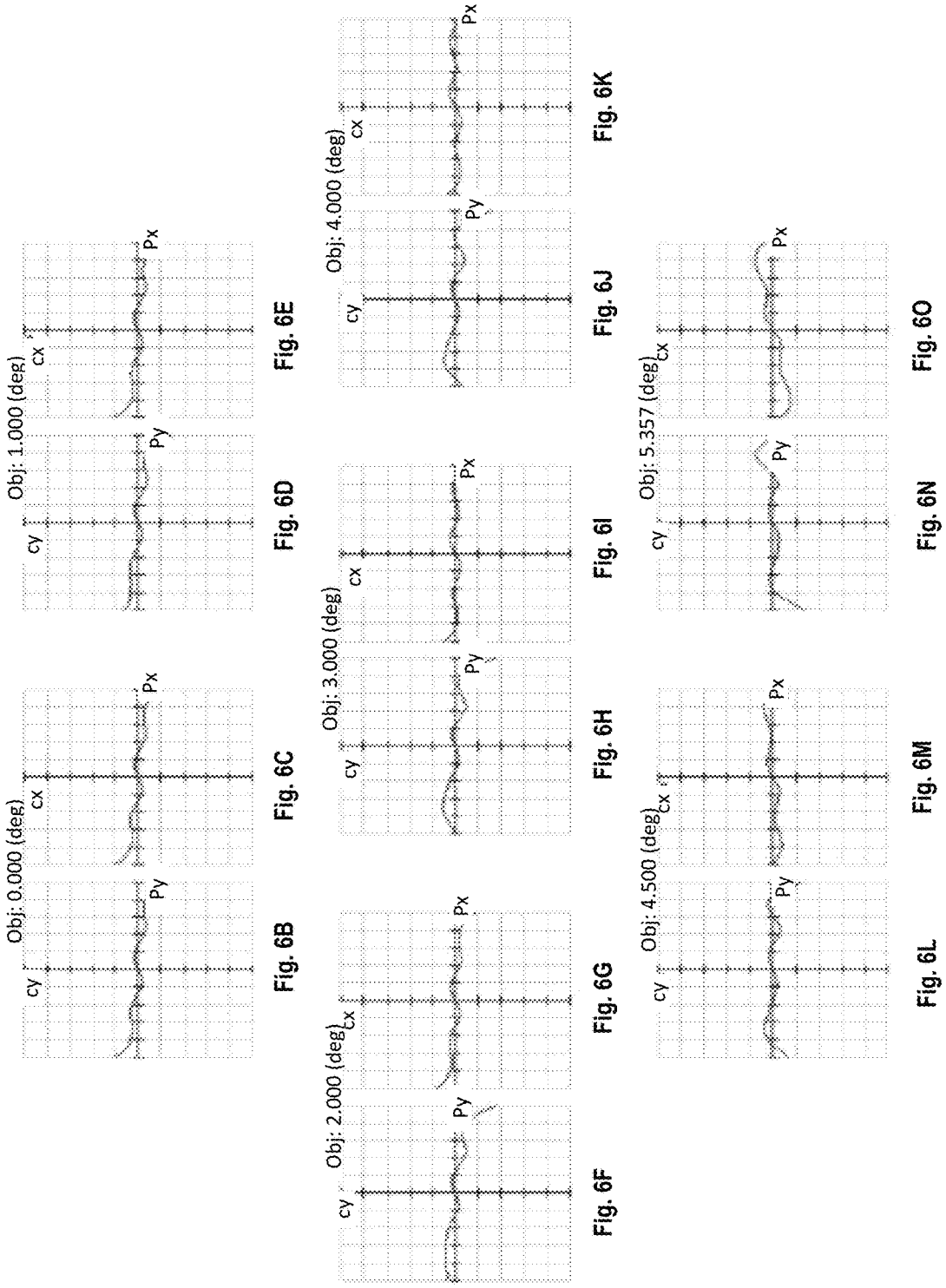
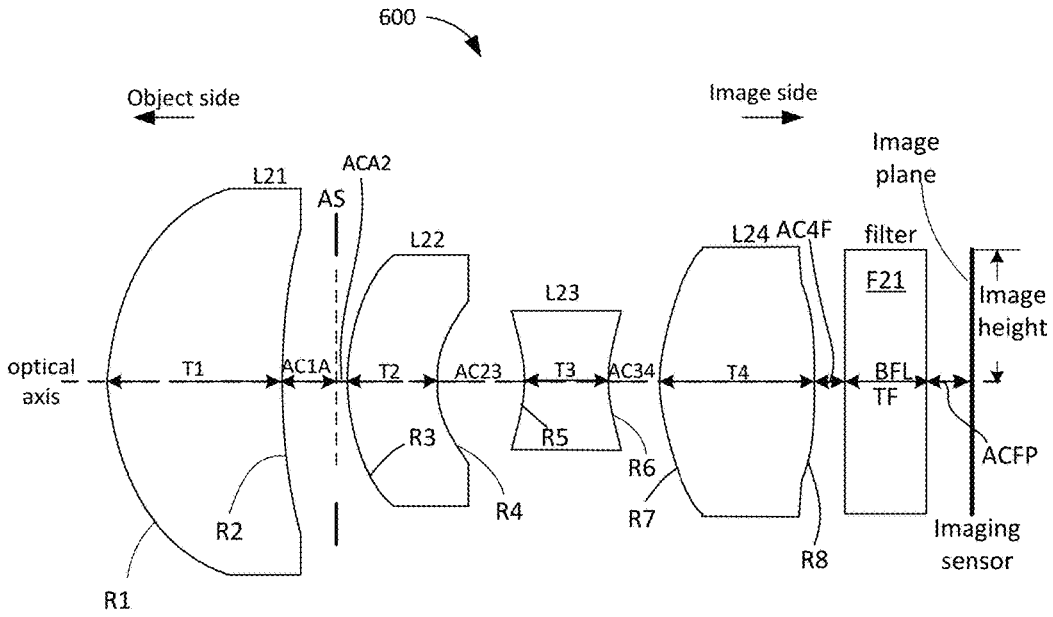


Fig. 6B Fig. 6C Fig. 6D Fig. 6E Fig. 6F Fig. 6G Fig. 6H Fig. 6I Fig. 6J Fig. 6K Fig. 6L Fig. 6M Fig. 6N Fig. 6O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Object side
Image side
Image plane
L21
ACA2
AS
L22
L24
AC4F
filter
F21
L23
Image height
optical axis
T1
AC1A
T2
AC23
T3
AC34
T4
BFL
TF
R3
R5
R6
ACFP
R2
R4
R7
R8
Imaging sensor
R1

Figure 7A

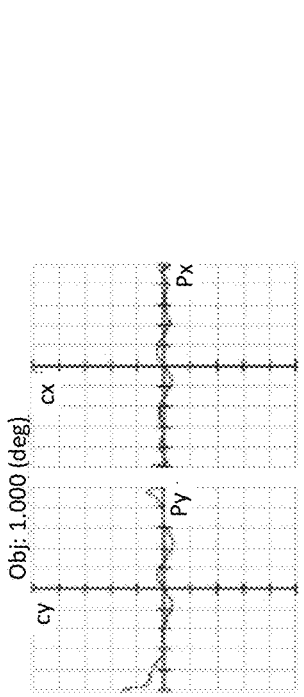


Fig. 7B

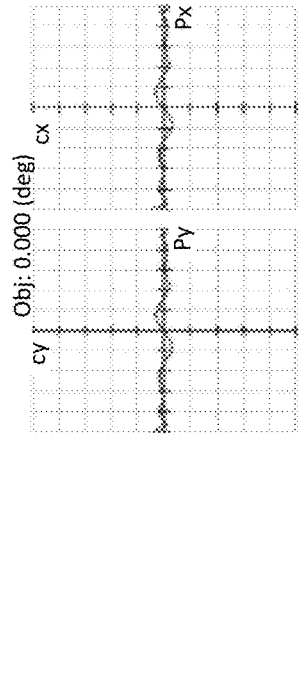


Fig. 7C

Fig. 7D

Fig. 7E

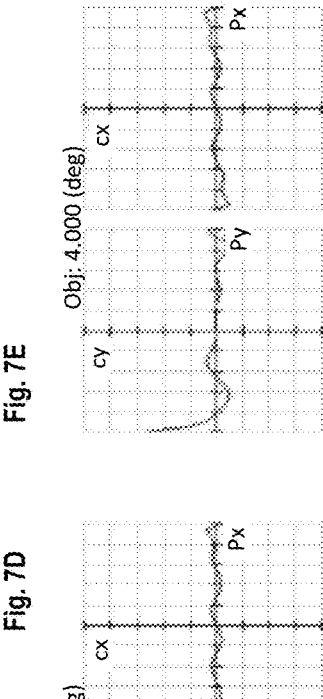


Fig. 7F

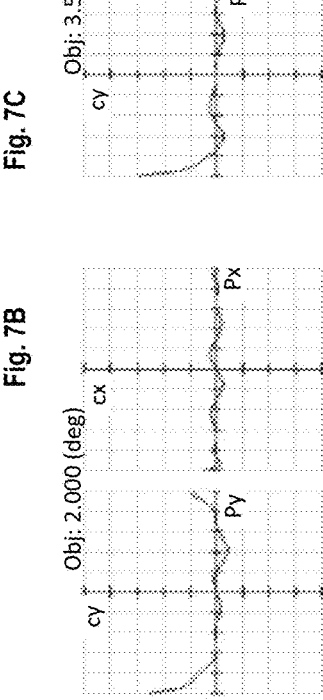
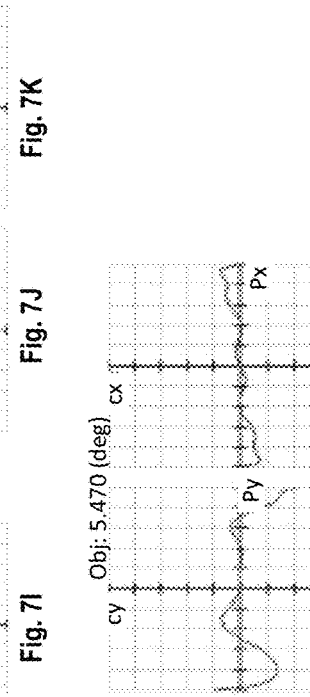


Fig. 7G

Fig. 7H

Fig. 7I



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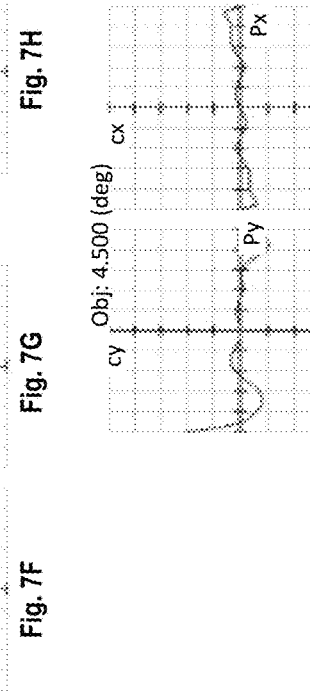
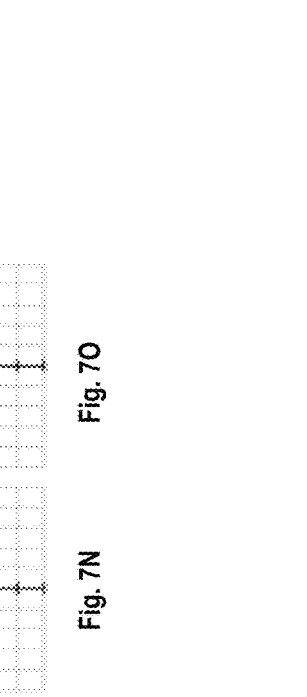


Fig. 7K

Fig. 7L

Fig. 7M



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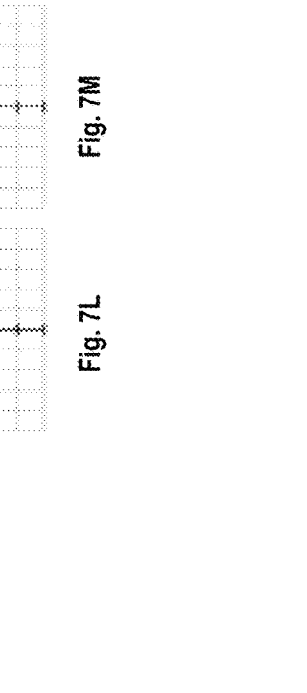

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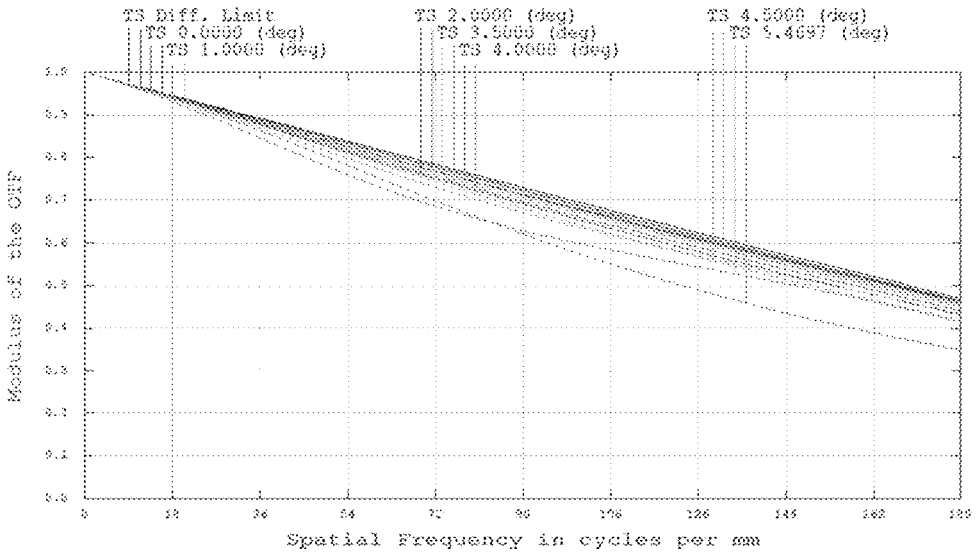
TS Diff. Limit
TS 0.0000 (deg)
TS 1.0000 (deg)
TS 2.0000 (deg)
TS 3.5000 (deg)
TS 4.0000 (deg)
TS 4.5000 (deg)
TS 5.4697 (deg)
Modulus of the OTF
Spatial Frequency in cycles per mm

Figure 7P

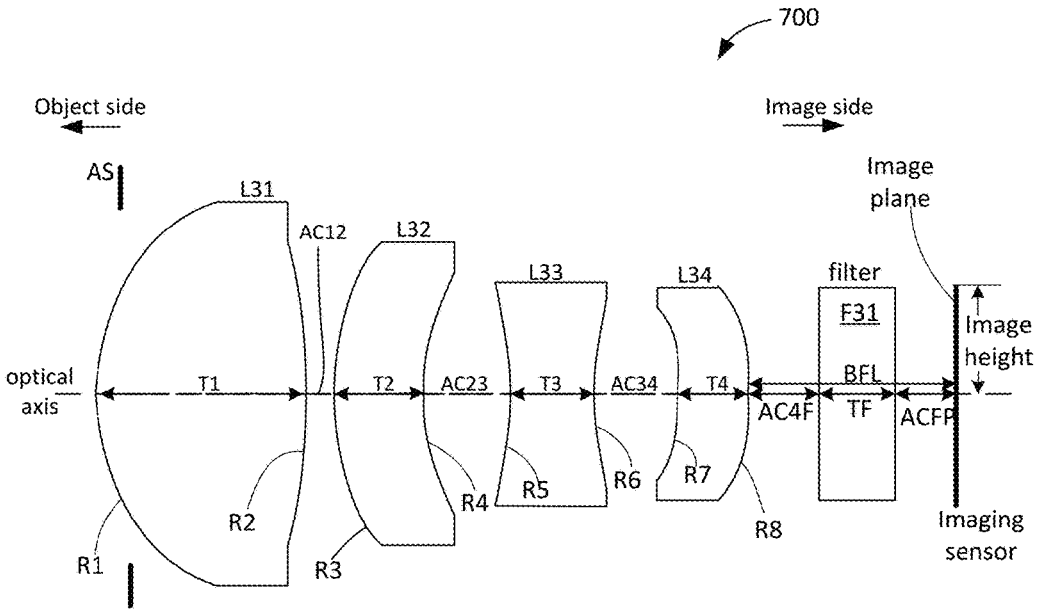
700
Object side
Image side
AS
L31
AC12
L32
L33
L34
filter
F31
Image plane
Image height
optical axis
T1
T2
AC23
T3
AC34
T4
AC4F
BFL
TF
ACFP
R1
R2
R3
R4
R5
R6
R7
R8
Imaging sensor

Figure 8A

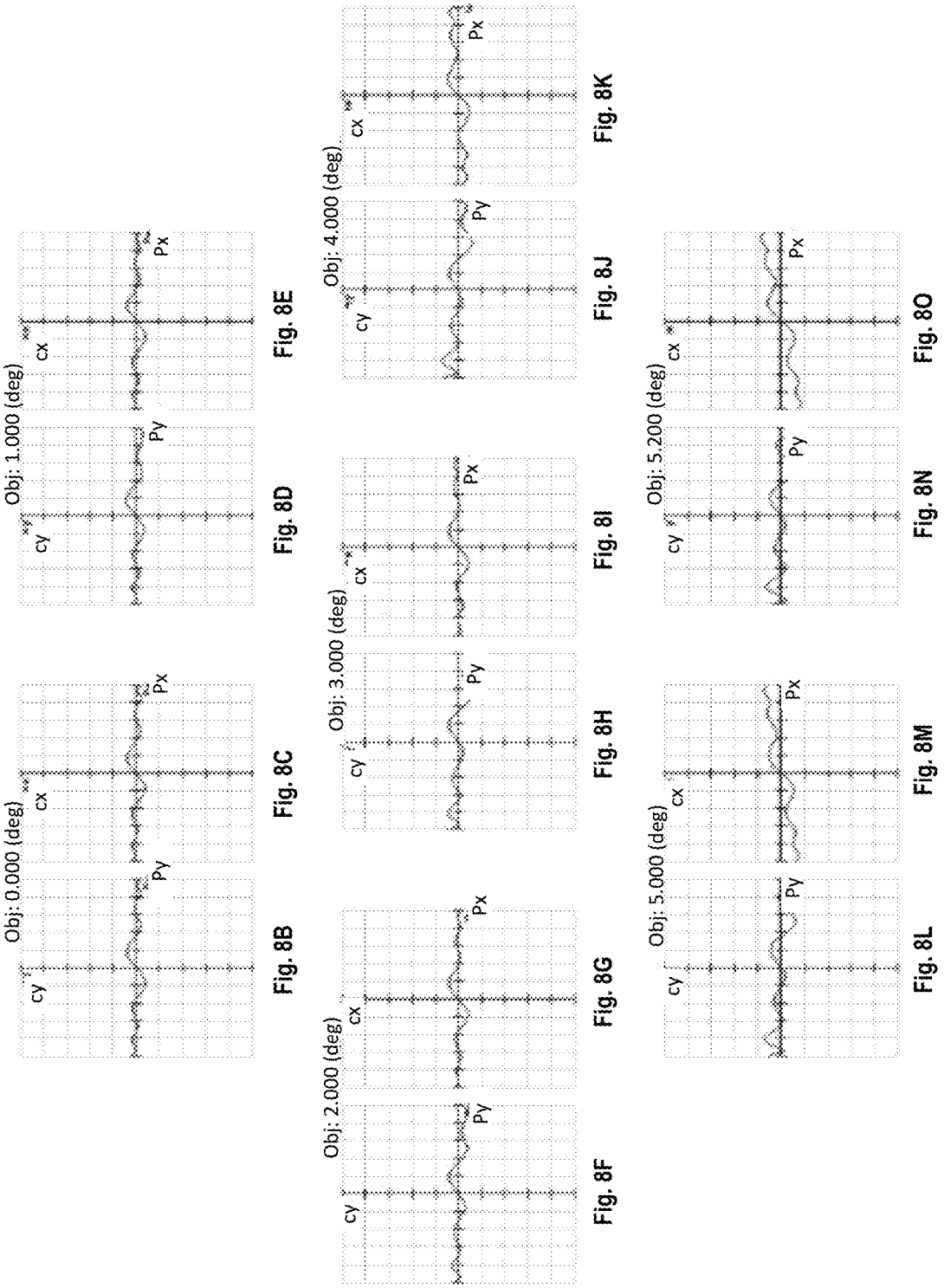

Fig. 8B Fig. 8C Fig. 8D Fig. 8E Fig. 8F Fig. 8G Fig. 8H Fig. 8I Fig. 8J Fig. 8K Fig. 8L Fig. 8M Fig. 8N Fig. 8O

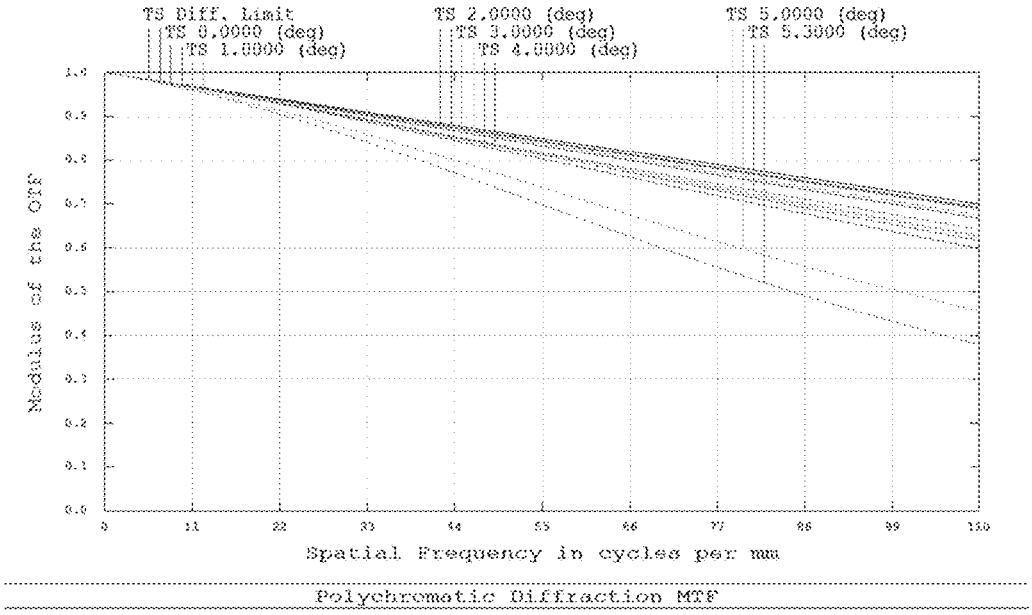
TS Diff. Limit
TS 0.0000 (deg)
TS 1.0000 (deg)
TS 2.0000 (deg)
TS 3.0000 (deg)
TS 4.0000 (deg)
TS 5.0000 (deg)
TS 5.3000 (deg)
Modulus of the OTF
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
11
22
33
44
55
66
77
88
99
110
Spatial Frequency in cycles per mm
Polychromatic Diffraction MTF

Figure 8P

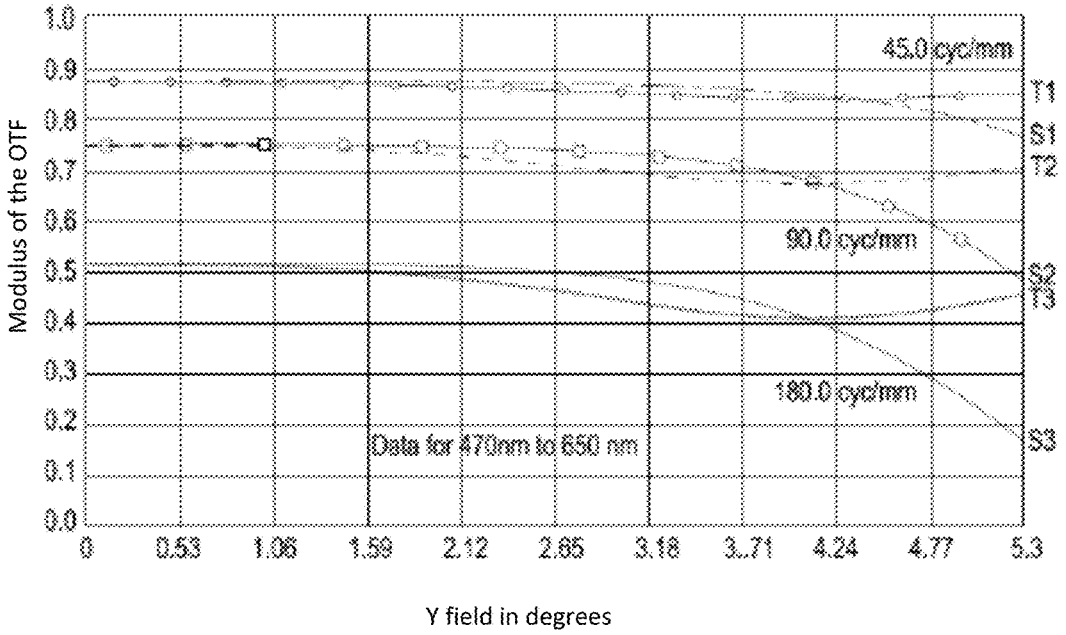
Modulus of the OTF
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
0.53
1.06
1.59
2.12
2.65
3.18
3.71
4.24
4.77
5.3
45.0 cyc/mm
90.0 cyc/mm
180.0 cyc/mm
Data for 470nm to 650 nm
T1
S1
T2
S2
T3
S3
Y field in degrees

Figure 8Q

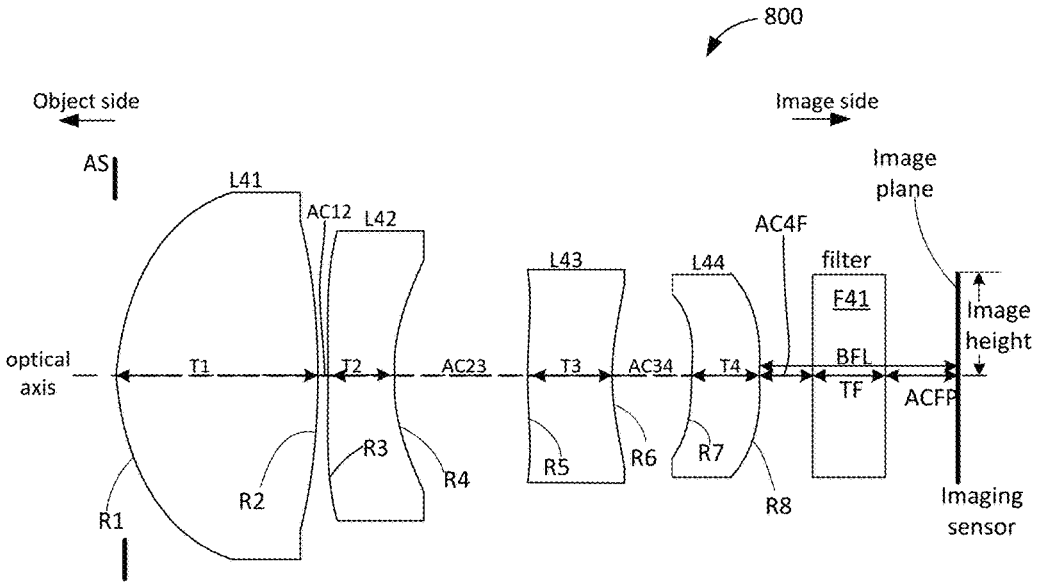
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Image side
AS
L41
AC12
L42
L43
L44
AC4F
filter
F41
Image plane
Image height
optical axis
T1
T2
AC23
T3
AC34
T4
BFL
TF
ACFP
R1
R2
R3
R4
R5
R6
R7
R8
Imaging sensor

Figure 9A

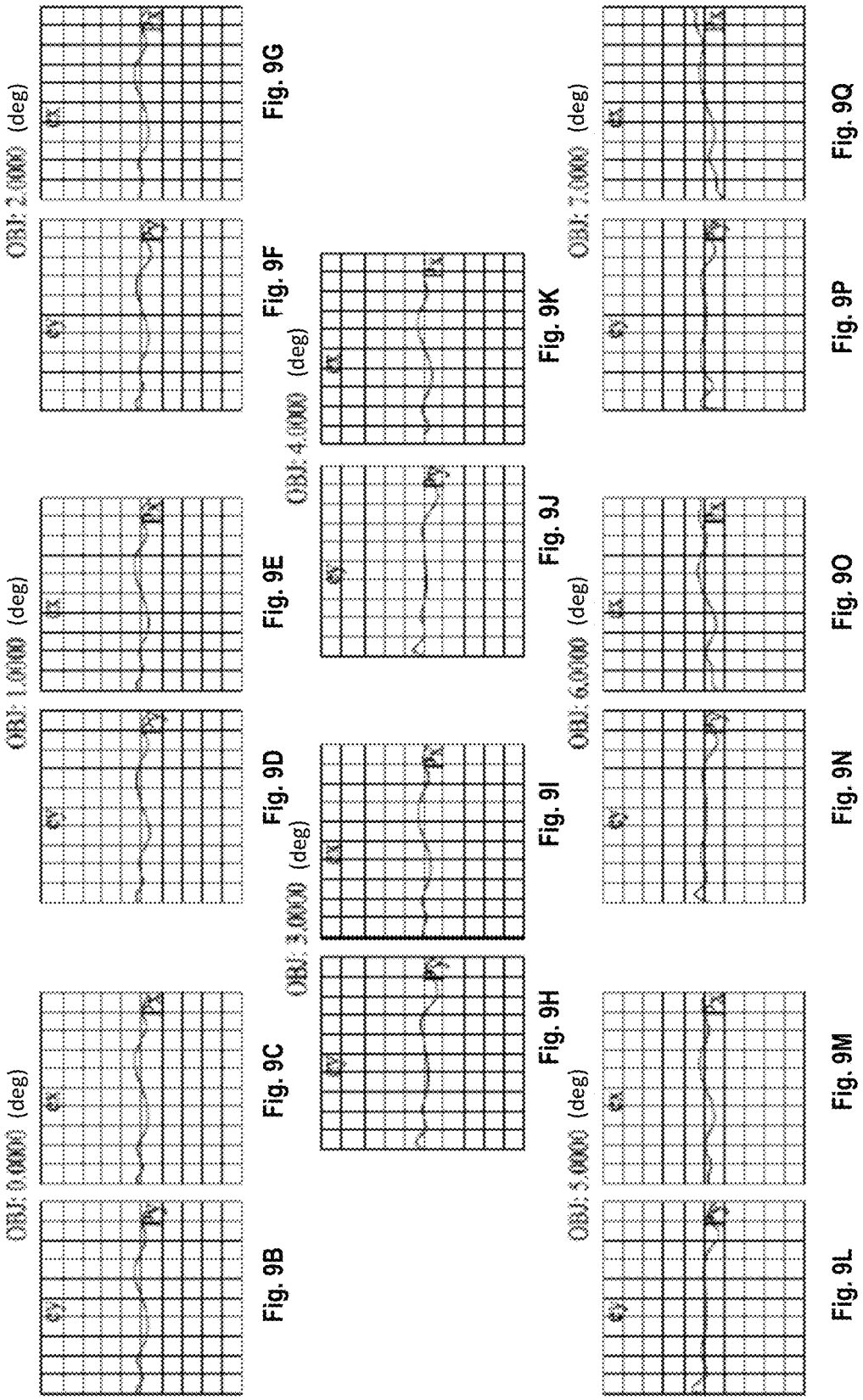


Fig. 9B Fig. 9C Fig. 9D Fig. 9E Fig. 9F Fig. 9G

Fig. 9H Fig. 9I Fig. 9J Fig. 9K

Fig. 9L Fig. 9M Fig. 9N Fig. 9O Fig. 9P Fig. 9Q

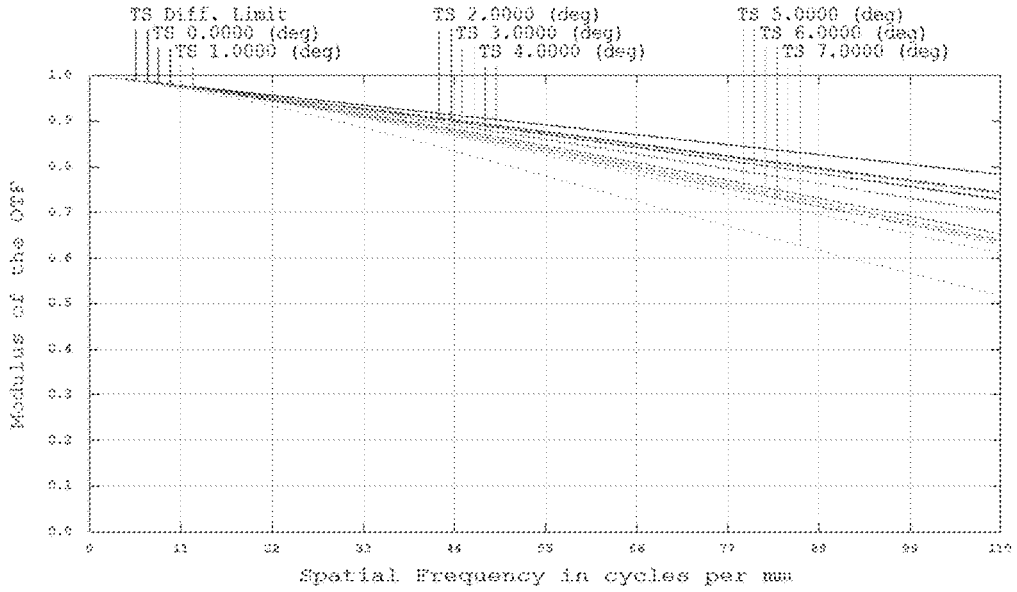


Figure 9R

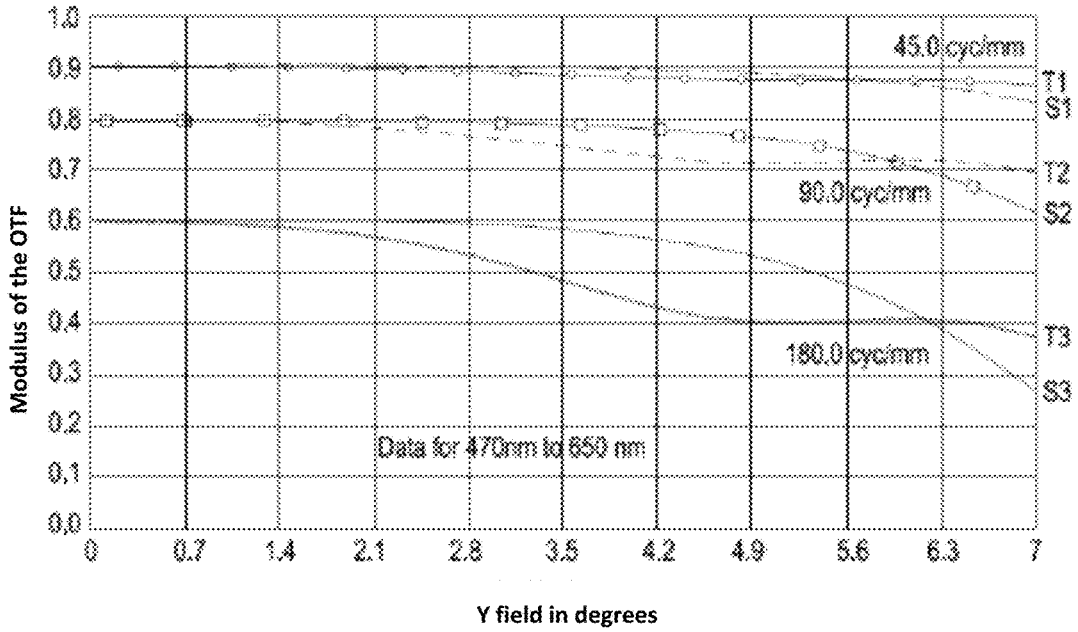
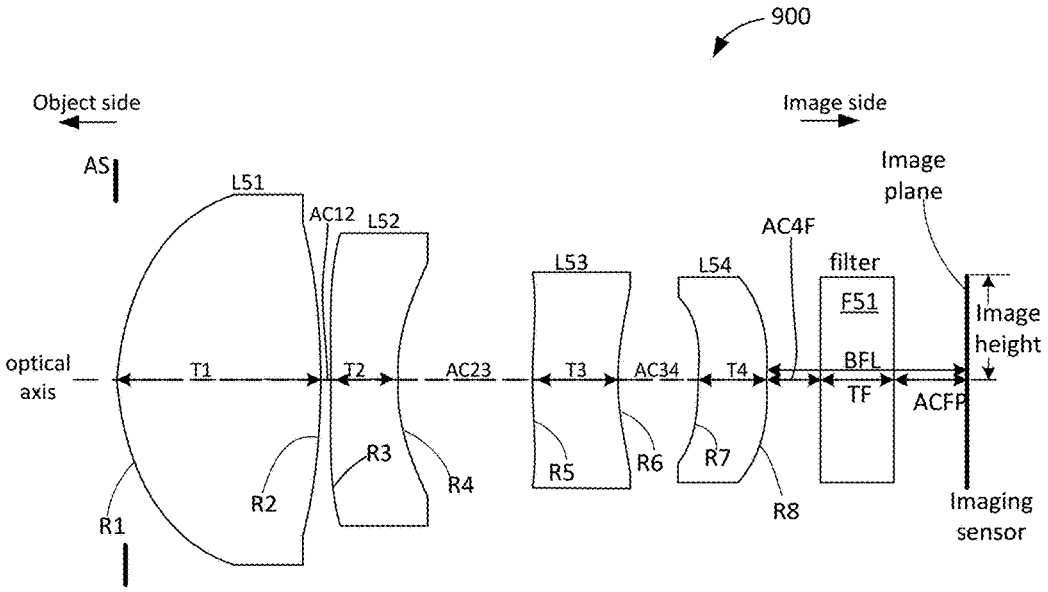


Figure 9S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L52
L53
L54
AC4F
filter
F51
Image plane
Image height
optical axis
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T2
AC23
T3
AC34
T4
BFL
TF
ACFP
R1
R2
R3
R4
R5
R6
R7
R8
Imaging sensor

Figure 10A

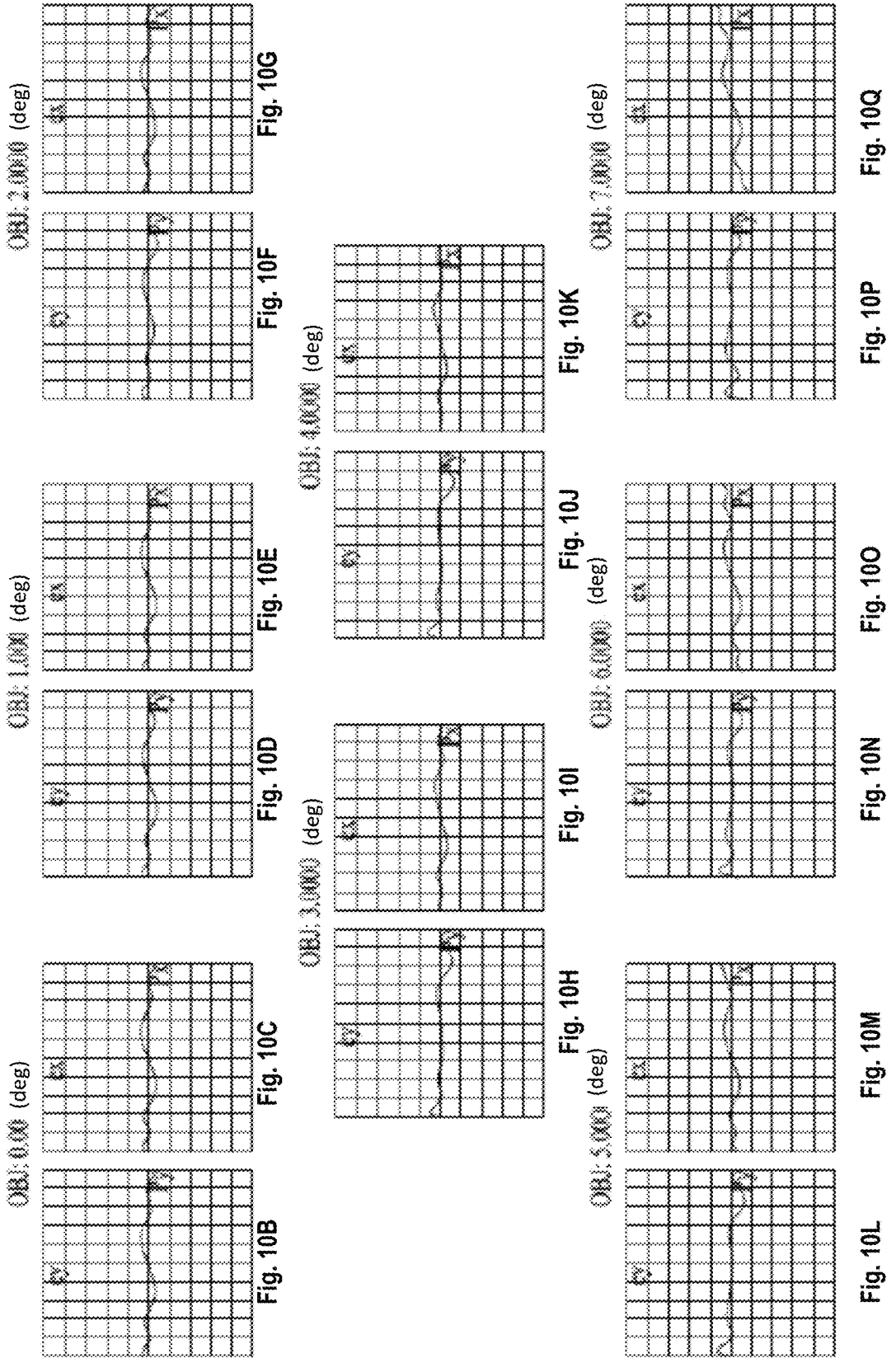


Fig. 10B Fig. 10C Fig. 10D Fig. 10E Fig. 10F Fig. 10G

Fig. 10H Fig. 10I Fig. 10J Fig. 10K

Fig. 10L Fig. 10M Fig. 10N Fig. 10O Fig. 10P Fig. 10Q

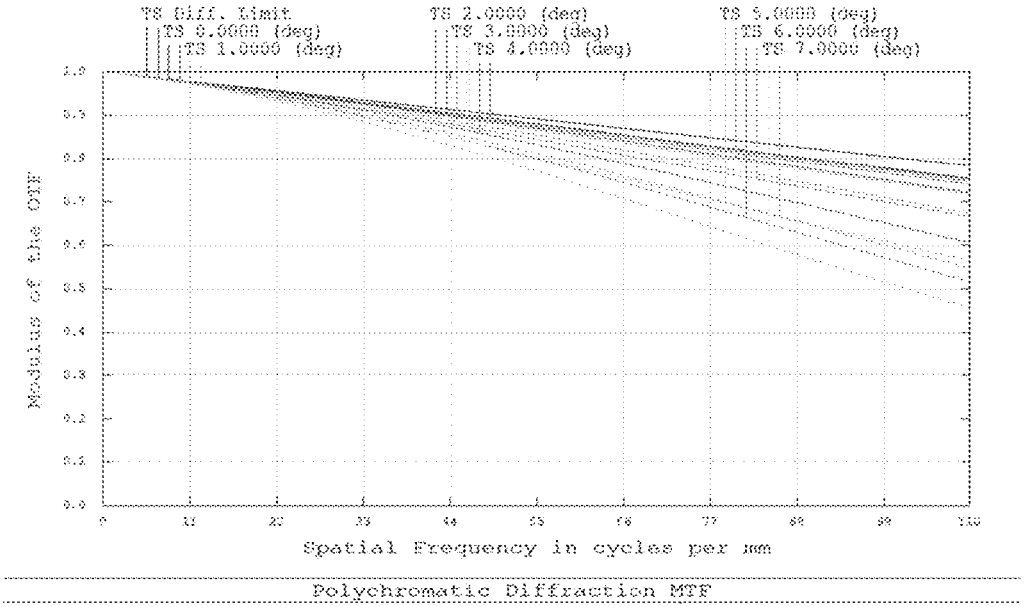


Figure 10R

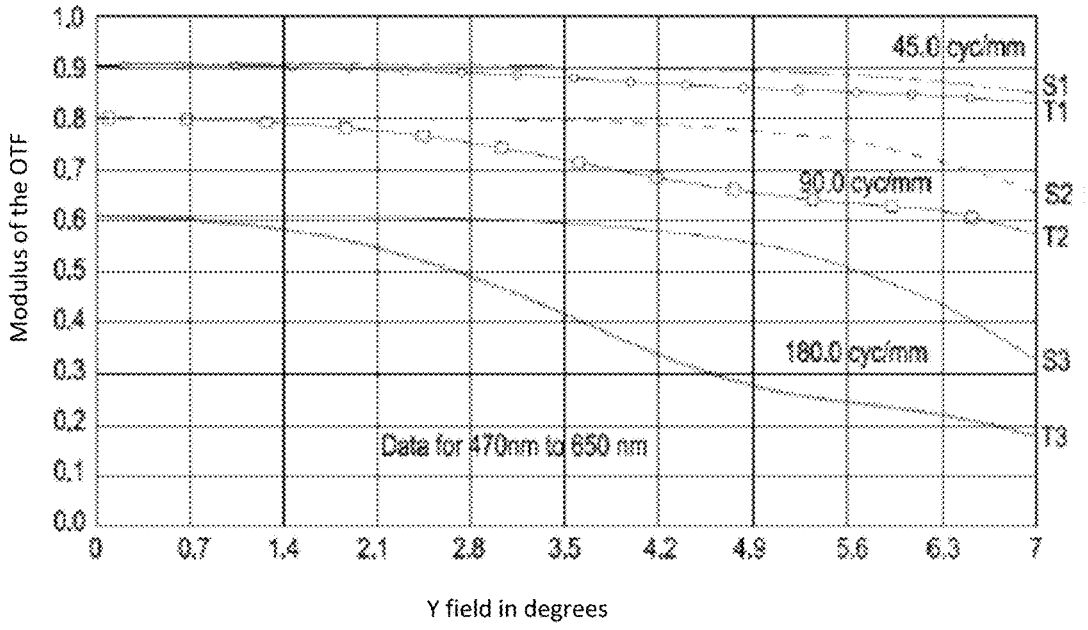


Figure 10S

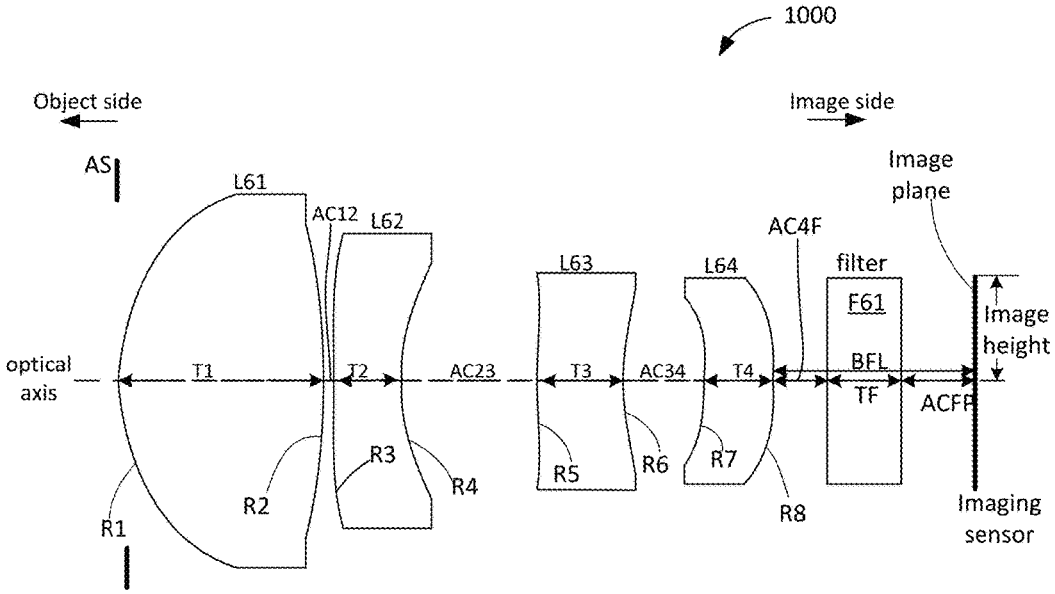

1000
Object side
Image side
AS
L61
AC12
L62
L63
L64
AC4F
filter
F61
Image plane
Image height
optical axis
T1
T2
AC23
T3
AC34
T4
BFL
TF
ACFP
R1
R2
R3
R4
R5
R6
R7
R8
Imaging sensor

Figure 11A

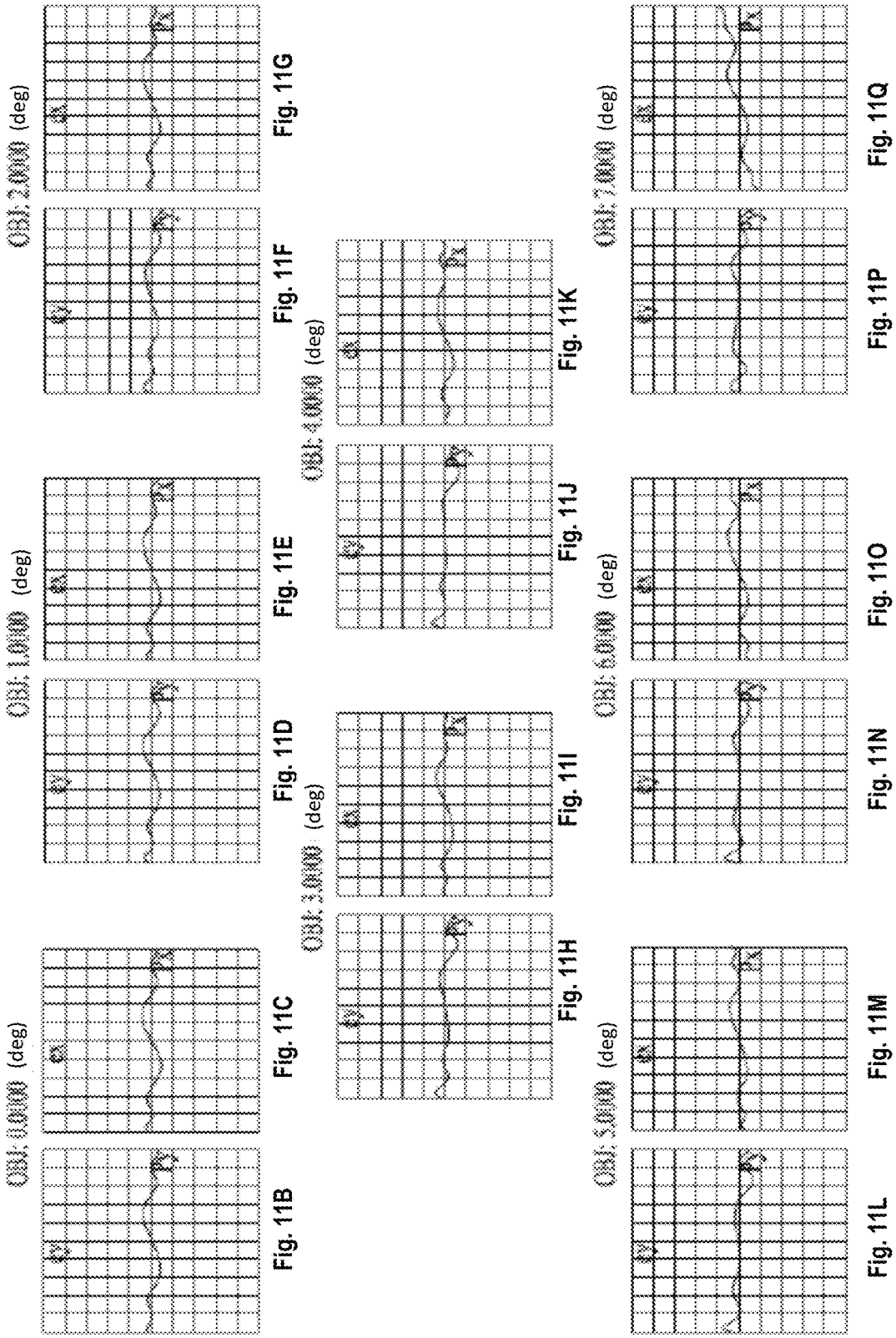


Fig. 11B Fig. 11C Fig. 11D Fig. 11E Fig. 11F Fig. 11G Fig. 11H Fig. 11I Fig. 11J Fig. 11K Fig. 11L Fig. 11M Fig. 11N Fig. 11O Fig. 11P Fig. 11Q

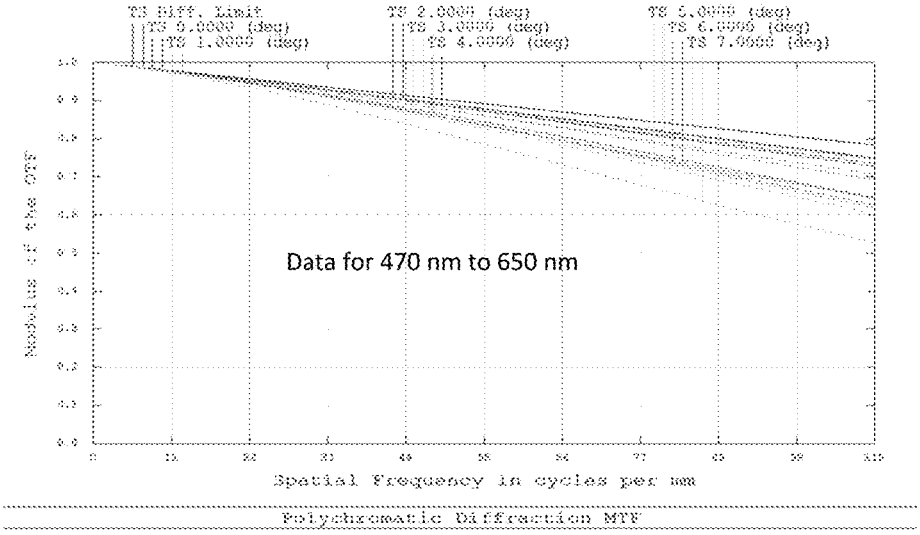


Figure 11R

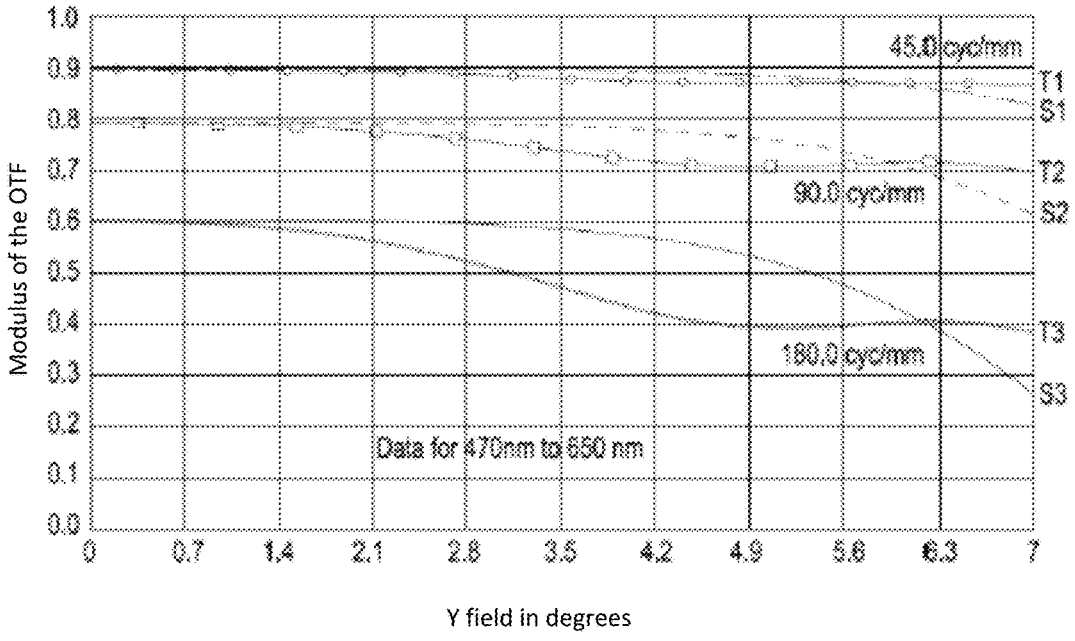


Figure 11S

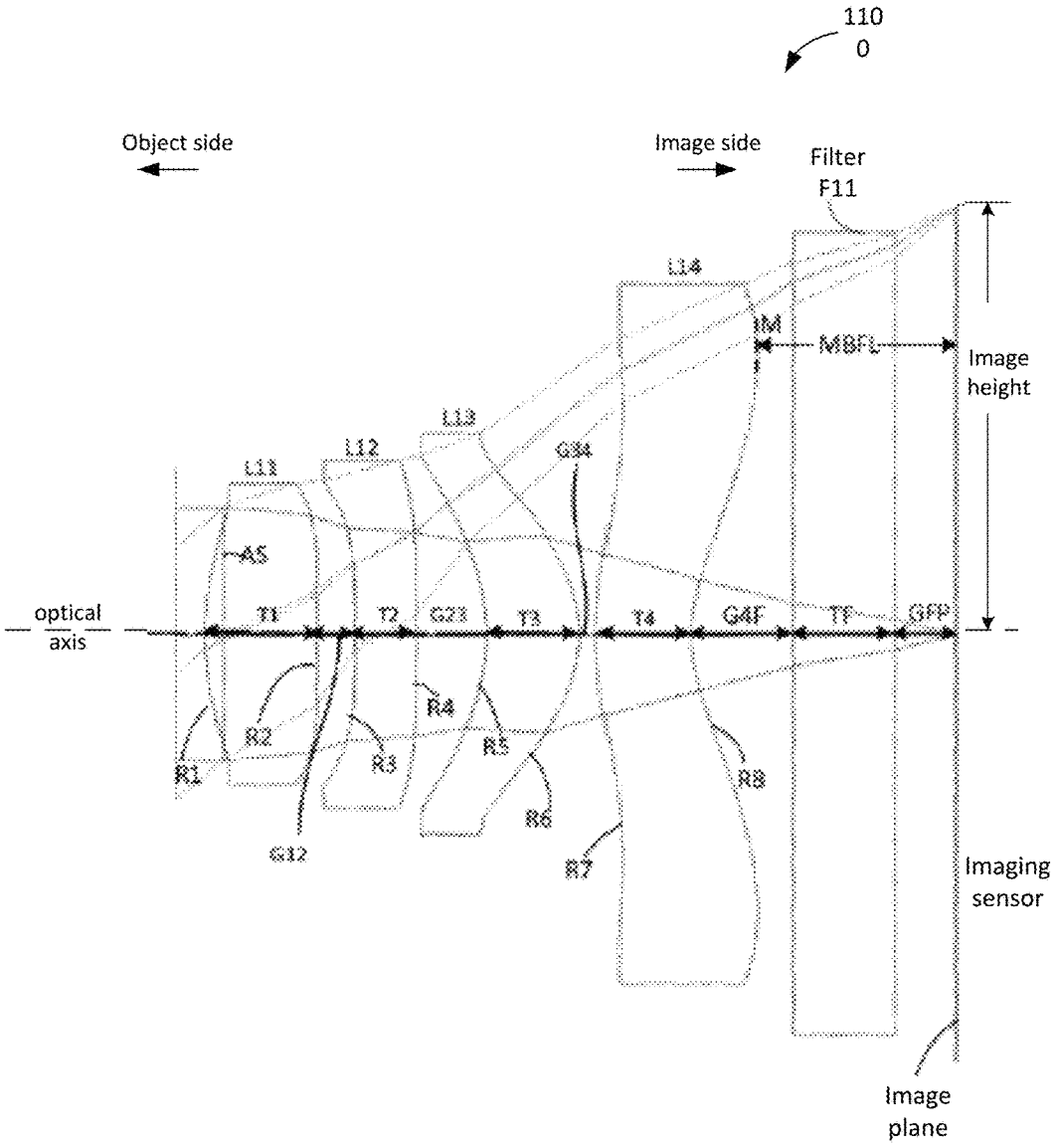

110
0
Object side
Image side
Filter
F11
L14
IM
MBFL
Image
height
L13
L12
L11
G34
AS
optical
axis
T1
T2
G23
T3
T4
G4F
TF
GFP
R4
R2
R3
R5
R1
R8
R6
G12
R7
Imaging
sensor
Image
plane

Figure 12A

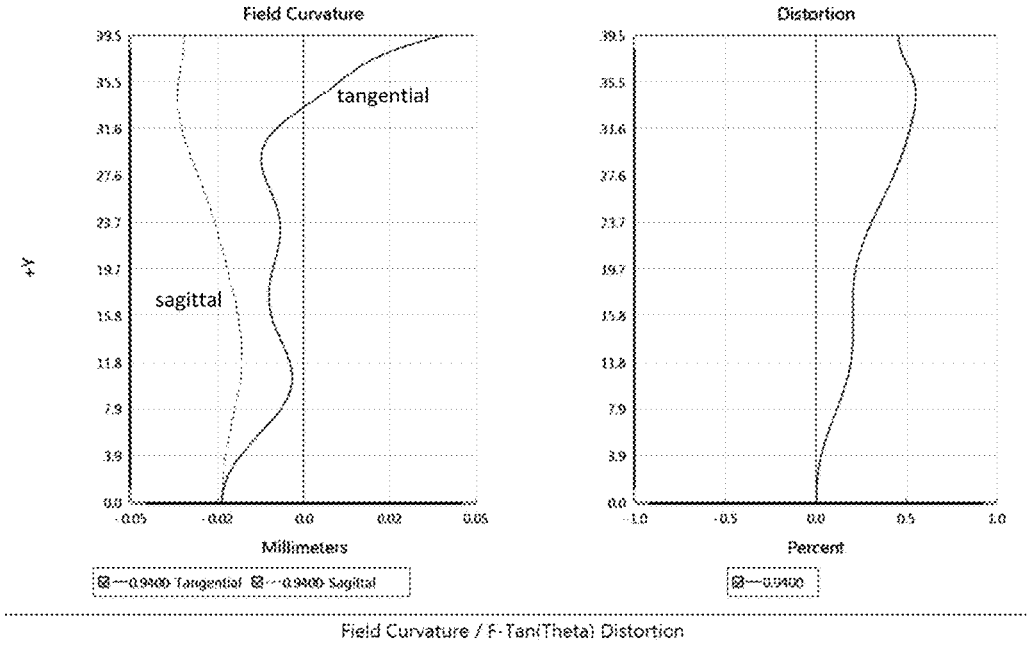


Figure 12B

Figure 12C

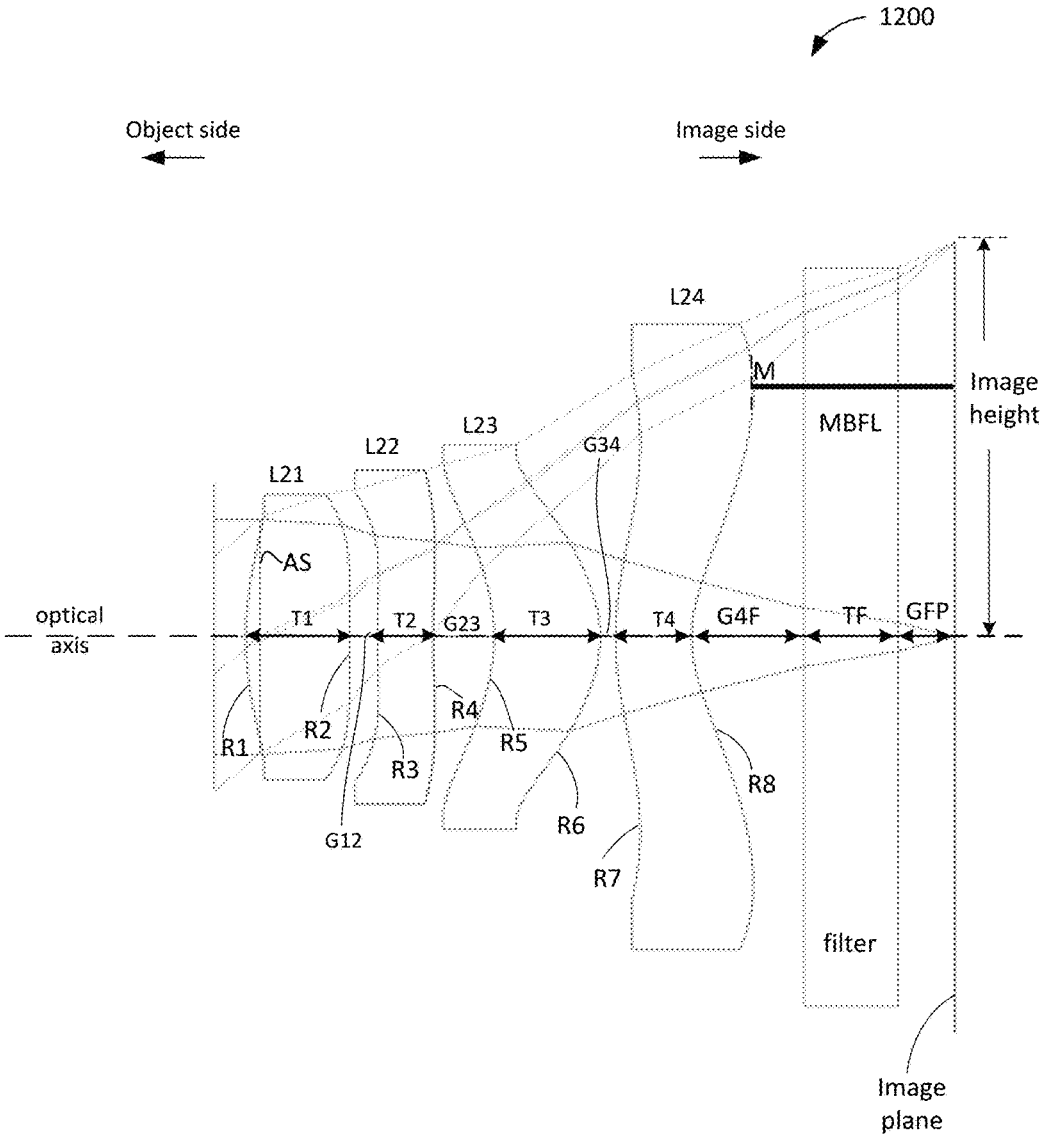
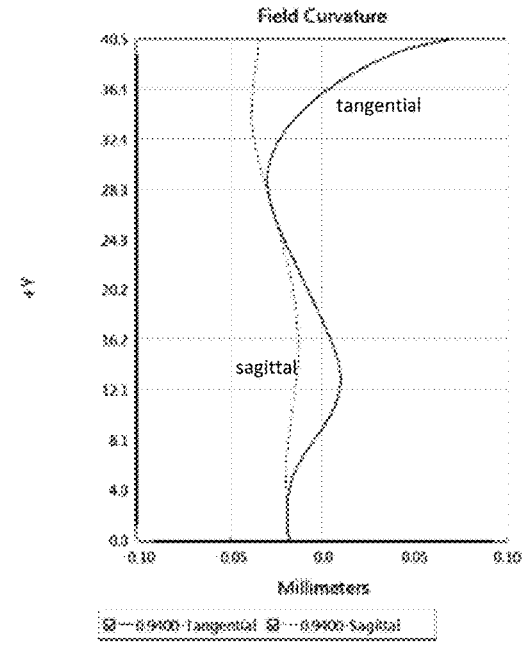
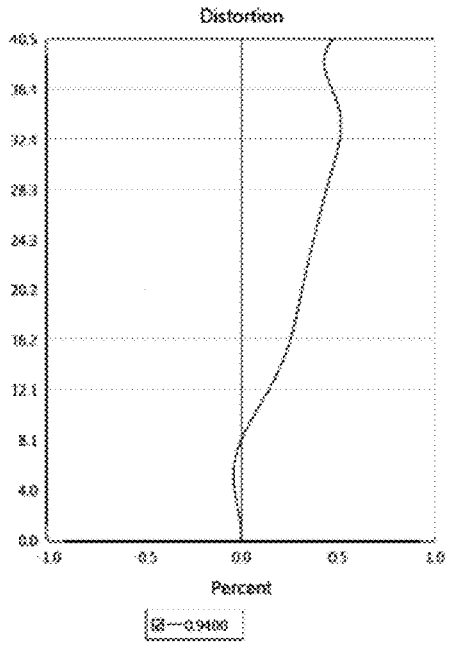

1200
Object side
Image side
L24
M
MBFL
Image height
L23
L22
G34
L21
AS
optical axis
T1
T2
G23
T3
T4
G4F
TF
GFP
R1
R2
R3
R4
R5
R6
R7
R8
G12
filter
Image plane

Figure 13A





Field Curvature / F-Tan(Theta) Distortion

Figure 13B

Figure 13C

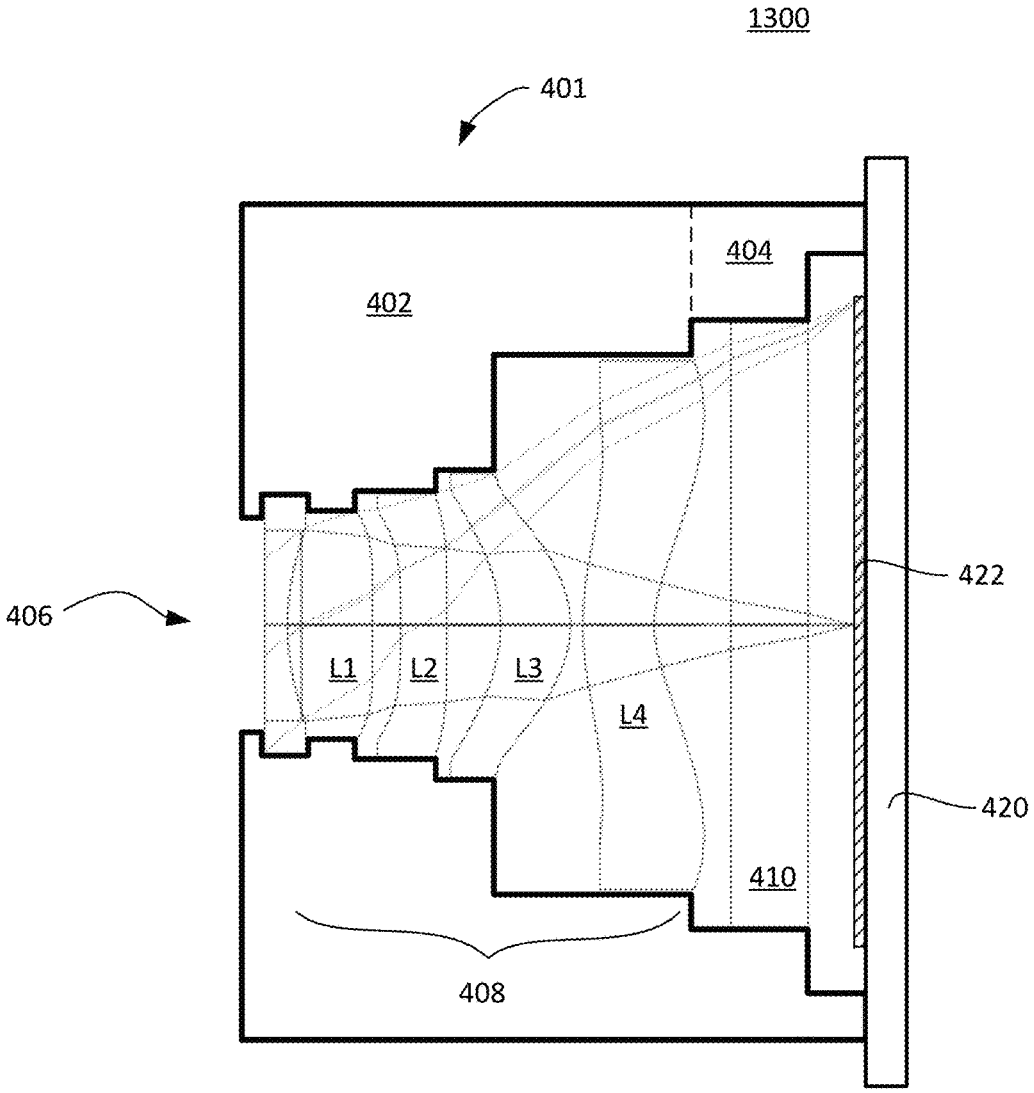


Figure 14

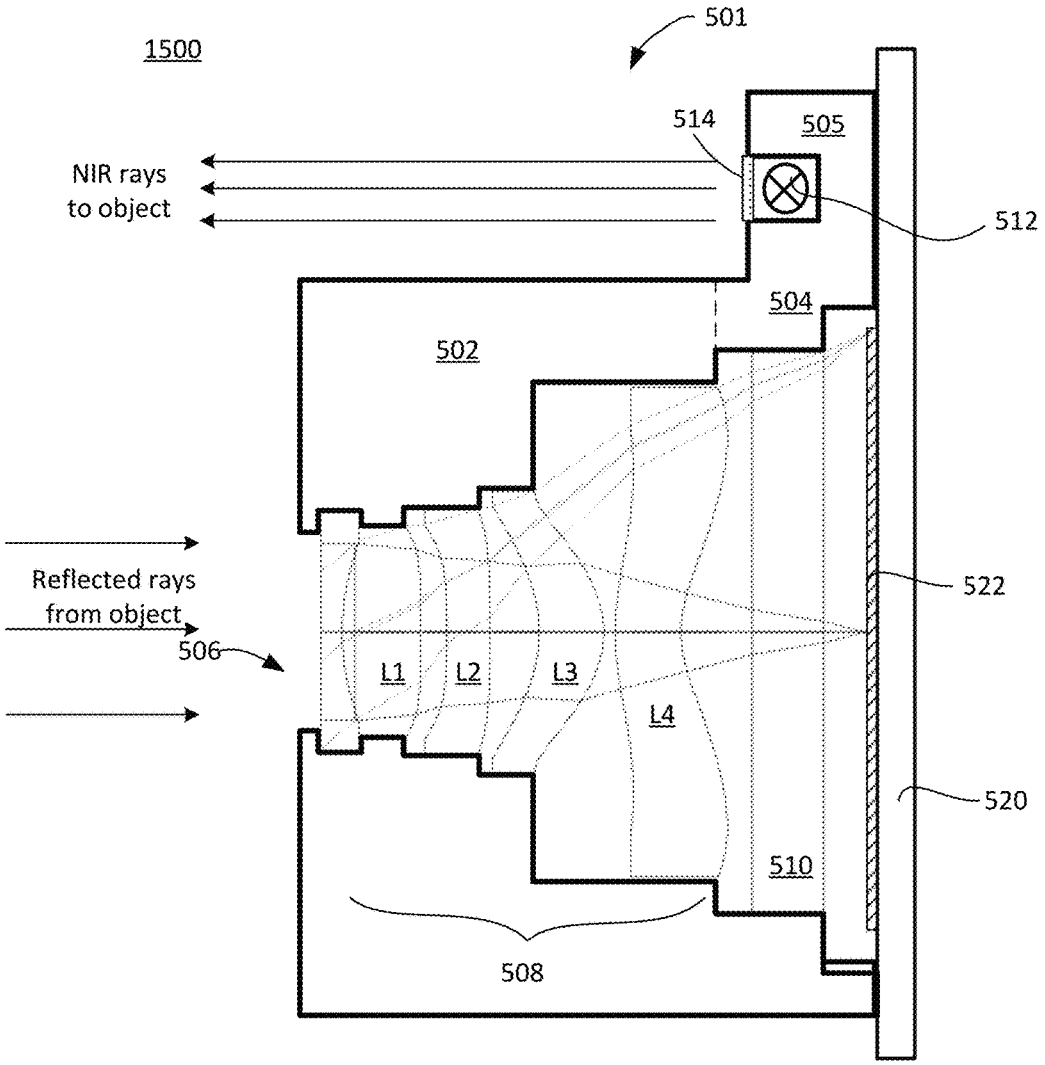

1500
501
514
505
NIR rays
to object
512
504
502
Reflected rays
from object
506
522
L1
L2
L3
L4
520
510
508

Figure 15

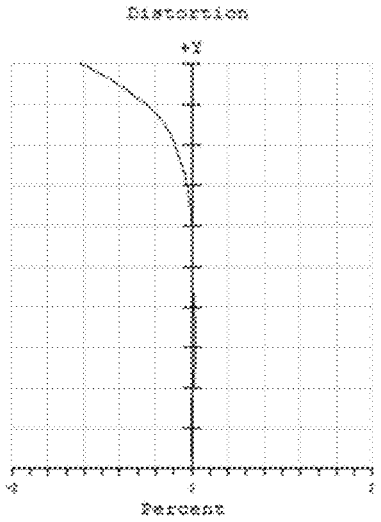


Figure 16A

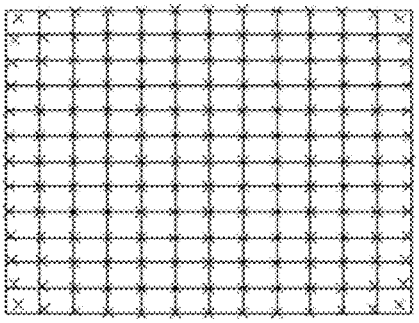


Figure 16B

NEAR-INFRARED LENS FOR CAMERAS IN MOBILE DEVICES

CROSS-REFERENCES TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 15/829,330, filed Dec. 1, 2017, which is a divisional of U.S. patent application Ser. No. 14/746,772, filed Jun. 22, 2015, now U.S. Pat. No. 9,864,168, which claims the benefit of U.S. Provisional Patent Application No. 62/015,867, filed Jun. 23, 2014, U.S. Provisional Patent Application No. 62/052,181, filed Sep. 18, 2014, and U.S. Provisional Patent Application No. 62/061,516, filed Oct. 8, 2014, the contents of which are hereby incorporated by reference in their entirety.

BACKGROUND OF THE INVENTION

The present disclosure relates to optical lens systems, and more particularly to near infrared optical imaging lens systems having three lens elements and four lens elements for cameras incorporated in mobile electronic devices.

Mobile electronic devices with built-in digital cameras are becoming increasingly popular. Along with trends of downsizing in digital cameras and cell phones and recent technological advances in charge coupled devices (CCD) and CMOS imaging sensors, optical lens systems also need to reduce their size. However, the size reduction of the optical imaging lens systems also has to take into account optical performance requirements.

Wavelengths longer than 700 nm are not directly perceived by human eyes. These wavelengths have the characteristics of anti jamming capability, low cost, low power consumption, and undetectability to a human eye. They are often used in remote control devices, infrared detection systems, and the like. In recent years, interactive electronic devices have been developed using infrared (IR) detectors or near infrared (NIR) detectors to detect a user movement for achieving user interactions.

The present invention relates to NIR imaging lens systems having three lens elements and four lens elements.

SUMMARY OF THE INVENTION

Certain embodiments of the present invention relate to an optical imaging system having three lens elements. In some embodiments, an optical imaging lens system includes, in order from an object side to an image side, an aperture stop, a first lens element, a second lens element, and a third lens element arranged along an optical axis. The first lens element has a positive refractive power, the second lens element has a negative refractive power, the third lens element has a convex object-side surface in a vicinity of the optical axis and a concave object-side surface near the outer circumference. In some embodiments, the first, second, and third lens elements are made of a same material; and the optical imaging system only has three lens elements having a refractive power.

In another embodiments, an optical imaging lens system includes, in order from an object side to an image side, a first lens element, a second lens element, a third lens element, and a fourth arranged along an optical axis. The first lens element has a positive refractive power, the second lens element has a negative refractive power, the third lens element has a negative refractive power, and the fourth lens element has a positive refractive power. The fourth lens element has a convex object-side surface in a vicinity of the optical axis and a concave object-side surface near the outer circumference. In some embodiments, the first, second, third, and fourth lens elements are made of a same material, and the optical imaging system only has four lens elements having a refractive power.

The following description, together with the accompanying drawings, will provide a better understanding of the nature and advantages of the claimed invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a cross section view of an exemplary lens element to explain the terms used in the present description.

FIG. **2**A is a simplified cross-section view of a three-element optical lens system according to an embodiment of the present invention.

FIGS. **2**B and **2**C are graphs illustrating the respective astigmatic field curvatures and distortion in the embodiment of FIG. **2**A.

FIG. **3**A is a simplified cross-section view of a four-element optical lens system according to an embodiment of the present invention.

FIGS. **3**B and **3**C are graphs illustrating the respective astigmatic field curvatures and distortion in the embodiment of FIG. **3**A.

FIG. **4** is a simplified cross-section view of a four-element telecentric optical lens system according to an embodiment of the present invention.

FIG. **5**A is a simplified cross-section view of a four-element telecentric optical lens system according to another embodiment of the present invention.

FIG. **5**B is a MTF graph for the four-element telecentric optical lens system shown in FIG. **5**A.

FIG. **6**A is a simplified cross-section view of a four-element optical lens system according to an embodiment of the present invention.

FIGS. **6**B-**6**O are a set of graphs illustrating transverse ray fan plots in the embodiment of FIG. **6**A.

FIG. **7**A is a simplified cross-section view of a four-element optical lens system according to an embodiment of the present invention.

FIGS. **7**B-**7**O are a set of graphs illustrating the transverse ray fan plot in the embodiment of FIG. **7**A.

FIG. **7**P is graph illustrating the modulus of the optical transfer function as a function of the spatial frequency (cycles/mm) in the embodiment of FIG. **7**A.

FIG. **8**A is a simplified cross-section view of a four-element optical lens system according to an embodiment of the present invention.

FIGS. **8**B-**8**O are a set of graphs illustrating the transverse ray fan plot in the embodiment of FIG. **8**A.

FIG. **8**P is a set of graphs illustrating the modulus of the optical transfer function as a function of the spatial frequency (cycles/mm) in the embodiment of FIG. **8**A.

FIG. **8**Q is graph illustrating the modulus of the optical transfer function (OTF) as a function of the field in the embodiment of FIG. **8**A.

FIG. **9**A is a simplified cross-section view of a four-element optical lens system according to an embodiment of the present invention.

FIG. **9**B-**9**Q are a set of graphs illustrating transverse ray fan plots in the embodiment of FIG. **9**A.

FIG. **9**R is a set of graphs illustrating the modulus of the optical transfer function as a function of the spatial frequency (cycles/mm) in the embodiment of FIG. **9**A.

FIG. **9**S is graph illustrating the modulus of the optical transfer function (OTF) as a function of the field in the embodiment of FIG. **9**A.

FIG. **10**A is a simplified cross-section view of a four-element optical lens system according to an embodiment of the present invention.

FIGS. **10**B-**10**Q are a set of graphs illustrating the transverse ray fan plot in the embodiment of FIG. **10**A.

FIG. **10**R is a set of graphs illustrating the modulus of the optical transfer function as a function of the spatial frequency (cycles/mm) in the embodiment of FIG. **10**A.

FIG. **10**S is graph illustrating the modulus of the optical transfer function (OTF) as a function of the field in the embodiment of FIG. **10**A.

FIG. **11**A is a simplified cross-section view of a four-element optical lens system according to an embodiment of the present invention.

FIG. **11**B-**11**Q are a set of graphs illustrating transverse ray fan plots in the embodiment of FIG. **11**A.

FIG. **11**R is a set of graphs illustrating the modulus of the optical transfer function as a function of the spatial frequency (cycles/mm) in the embodiment of FIG. **11**A.

FIG. **11**S is graph illustrating the modulus of the optical transfer function (OTF) as a function of the field in the embodiment of FIG. **11**A.

FIG. **12**A is a simplified cross-section view of a four-element optical lens system according to an embodiment of the present invention.

FIG. **12**B is a set of graphs illustrating the astigmatism for the sagittal and tangential image surface in the embodiment of FIG. **12**A.

FIG. **12**C is the optical distortion of the embodiment of FIG. **12**A.

FIG. **13**A is a simplified cross-section view of a four-element optical lens system according to an embodiment of the present invention.

FIG. **13**B is a set of graphs illustrating the astigmatism for the sagittal and tangential image surface in the embodiment of FIG. **13**A.

FIG. **13**C is the optical distortion of the embodiment of FIG. **13**A.

FIG. **14** is a simplified cross-section view of a four-element optical lens system according to an embodiment of the present invention.

FIG. **15** is a simplified cross-section view of a four-element optical lens system according to an embodiment of the present invention.

FIG. **16**A is a graph illustrating the distortion and FIG. **16**B is a simplified diagram of an example raster TV distortion.

DETAILED DESCRIPTION OF SPECIFIC EMBODIMENTS

Certain embodiments of the present invention relate to three-element optical lens systems and other embodiments of the present invention relate to four-element optical lens systems. These three-element and four element optical systems have broad applications in electronic devices, such as a mobile phone, a digital still camera, a digital video camera, a tablet, and the like, that use a CCD or a CMOS imaging sensor. Lens data and other parameters of specific embodiments are described below. Those skilled in the art with access to the present disclosure will recognize that other lens systems can also be designed within the scope of the claimed invention.

Definition of Terms

The term "lens element" refers to a single transparent mass of refractive material having two opposite refractive surfaces. The expression "a lens element with a positive refractive power negative refractive power)" refers to the refractive power in the vicinity of the optical axis of the lens element having a positive refractive power (or negative refractive power). A lens element having a convex (or concave) surface in a region refers to that region having a convex portion (or concave portion) with respect to the adjacent outer region in the radial direction of that region, and the region has a protruding (convex) or depressed (concave) surface with respect to the optical axis.

FIG. **1** provides an example cross-sectional view of a lens element to explain the terms used in the present description. As shown in FIG. **1**, "I" denotes the optical axis of an exemplary lens element **2** having rotational symmetry along the optical axis. The object side of the lens element has a convex surface in region A, a concave surface in region B, and a convex surface in regions C and D. Region A has a convex surface because the surface of the region A is protruding with respect to the adjacent radial outer region (i.e., region B) and in the direction of the optical axis. Region B is depressed in relation to adjacent region A, C, or D. Region C or D is protruding with respect to adjacent region E. The expression "area around the circumference" refers to imaging light rays passing through the area in the vicinity of the circumferential edge of the lens element, i.e., the region C or D. The imaging light rays may include a chief ray Lc and marginal rays Lm. The expression "area in the vicinity of the optical axis" refers to imaging light passing through the region of the optical axis, i.e., the region A. The expression "area in a vicinity of an outer circumference of a lens element" means in the vicinity of the circumferential region on the surface of the lens element only where the imaging light passes, such as the region C or D. In addition, the lens element may include an extension portion or flange E configured to mount the lens element to a lens barrel. The desired imaging light rays may not pass through the extended portion E. Although the extension portion E of the lens element may be part of the optical imaging system, a description and a sketch thereof will be omitted for the sake of brevity.

The "effective diameter" (also sometimes referred to as "clear aperture diameter" or "clear aperture") of a lens element refers to the diameter of the portion of the surface of the lens element that is shaped to contribute to optical performance. For example, some or all lens elements may be formed with a flange or other structure at the outer periphery for mechanical purposes (e.g., positioning and retention of the lens element), and it is to be understood that such a structure would be outside the effective diameter. Further, in some instances, the object-side and image-side surfaces of a single lens element may have different effective diameters. In some instances, portions of the surface of a lens element may be specified as convex or concave. Such portions can be symmetric about the optical axis, with a portion that is "near," or "in the vicinity of," the optical axis extending outward from the optical axis and a portion "near," or "in the vicinity of," the periphery extending inward from the effec-

tive diameter. Those of skill in the art will understand that a portion of the surface described as being near the optical axis (or near the peripheral edge) may extend outward (or inward) sufficiently far to provide the desired optical properties.

The telephoto ratio is defined as the ratio between the total length TTL measured from the object-side surface of the first lens element to the image plane along the optical axis and the effective focal length. An optical imaging lens having a telephoto ratio (TTL/EFL) of less than 1 is referred to as a telephoto lens.

Three Element Lens System

First Embodiment

FIG. **2**A is a simplified cross-section view of a three-element optical lens system **100** according to a first embodiment of the present invention. Optical lens system **100** comprises a first lens element L**1**, a second lens element L**2**, and a third lens element L**3**, in order from the object side to the image side along the optical axis. Each lens element L**1**-L**3** can be rotationally symmetric above the optical axis.

First lens element L**1** has a positive refractive power, a convex object-side surface, a convex image-side surface in the outer circumferential region, and a convex image-side surface in the vicinity of the optical axis. Second lens element L**2** has a negative refractive power, a concave object-side surface in the vicinity of the optical axis, a concave object-side surface in the outer circumferential region, a convex image-side surface in the vicinity of the optical axis, and a convex image-side surface in the outer circumferential region. Third lens element L**3** has a positive refractive power, a convex object-side surface in the vicinity of the optical axis and a concave object-side surface in the outer circumferential region, a concave surface on the image side along the optical axis, and a convex surface in the outer circumferential region. Optical lens system **100** further includes an aperture stop AS disposed in front of the first lens element L**1**, where the optical axis intersects the center of the aperture stop.

Optical lens system **100** also includes a filter configured to block the passage of light at visible wavelengths. In some embodiments, the filter filters out wavelengths below about 700 nm. The optical filter blocks shorter wavelengths of the visible spectrum and passes through wavelengths above about 700 nm. The filter improves the infrared performance of the imaging lens system **100** by reducing interference from other light sources. Although the filter is shown as a single filter disposed between the third lens element and the image plane, the filter can be disposed in any other locations and can have one or more filter elements.

Referring to FIG. **2**A, R**1** and R**2** are the respective object side and image side surface of first lens element L**1**. Likewise, R**3** and R**4** are the respective object side and image side surface of second lens element L**2**. Similarly, R**5** and R**6** are the respective object-side and image-side surface of third lens element L**3**.

In one embodiment, lens elements L**1**, L**2**, and L**3** each are made of the same material, which passes near infrared light having a wavelength about 900 nm. In another embodiment, the material of the lens elements L**1**, L**2**, and L**3** has a high absorption for visible light and a high transmission for near infrared light longer than 900 nm, preferably at 940 nm.

Still referring to FIG. **2**A, T**1** is the thickness of first lens element L**1**, T**2** is the thickness of the second lens element L**2**, and T**3** is the thickness of the third lens element L**3**. Thicknesses T**1**-T**3** are each measured along the optical axis. AC**12** is the air gap between the first and second lens elements, and AC**23** is the air gap between the second and third lens elements. Air gaps AC**12** and AC**23** are each measured along the optical axis. BFL denotes the back focal length, which is the distance between the image side of the third lens element and the image plane along the optical axis. BFL includes the thickness of the optical filter if the filter is disposed between the third lens element and the image plane. In the present disclosure, EFL denotes the effective focal length, which is also known as focal length. The focal length of an optical imaging system is defined as the distance over which collimated rays are brought to a focus. Hereinafter, the focal length is called effective focal length to distinguish from the back focal length (BFL).

In the following sections, ALT denotes the total thickness of the first to third lens elements, i.e., ALT=T**1**+T**2**+T**3**. AAG denotes the total width of the air gaps of the first to third lens elements along the optical axis, i.e., AAG=AC**12**+AC**23**.

According to certain embodiments of the present invention, in order to reduce the total length of the optical lens system, the following measures can be taken: reducing the thickness of the lens elements and the air gaps between them. However, it is difficult to reduce the total thickness of the lens elements while maintaining adequate optical performance. Accordingly, the first lens element is designed to have a positive refractive power, the second lens element is designed to have a negative refractive power, and the third lens element is designed to have a positive refractive power. In order to increase the production yield and reduce manufacturing costs all three lens elements can be made of the same material. In one embodiment, the optical lens material has an absorption spectrum of visible light with a wavelength in the range between 400 nm and 700 nm, while having high transmission for wavelengths above 850 nm.

According to the first embodiment, all three lens elements L**1**, L**2**, and L**3** can be made of the plastic material F52R and coated with an antireflective material optimized for near-infrared radiation. First lens element L**1** has a positive refractive power, a convex surface on the object-side in the vicinity of the optical axis, and a convex surface on the image-side in the vicinity of the optical axis. Second lens element has a negative refractive power, and the third lens element has a convex surface on the object in the vicinity of the optical axis, and a concave surface near the outer circumference. The object-side and image-side surfaces of the three lens elements are even aspheric. The combination of these three lens elements provides the desired lens system quality. Making the three lens elements of the same plastic can lower the manufacturing costs and simplify the manufacturing process.

Table 1A shows numeric lens data of the lens elements of optical lens system **100** according to the first embodiment of the present invention. All three lens elements are made of the plastic material F52R.

TABLE 1A

	Curvature Radius (1/mm)	Radius (mm)	Thickness/air gap (mm)	Refractive index	Abbe #	material
Object	Infinity		14400			
Aperture stop	Infinity		−0.12727			
Lens 1	0.868705	1.151139	0.51	1.535	55.63452	F52R
	−0.00598	−167.34	0.296489			
Lens 2	−0.90057	−1.11041	0.532417	1.535	55.63452	F52R
	−0.82053	−1.21872	0.510314			
Lens 3	0.812678	1.230499	0.361281	1.535	55.63452	F52R
	1.308748	0.764089	0.36			
filter	Infinity		0.210	1.52	64.2	
	Infinity		0.385			
Image plane	Infinity					

In the first embodiment, the effective focal length (EFL) is 2.5616 mm, the half field of view (HFOV) is 36.1 degrees. The F number is 2.22. The image height is 1.87 mm. The BFL is 0.955 mm. The entire length of the optical system **100** measured from the object-side surface of the first lens element to the image plane is 3.166 mm. The angular magnification is 1.303. The diameter of the aperture stop is 1.14 mm. The diameter of the filter is 3.374 mm.

The aspheric surface of the lens elements can be expressed using the following expression:

$$Z(Y) = \frac{Y^2}{R} \Big/ \left(1 + \sqrt{1 - (1+K)\frac{Y^2}{R^2}}\right) + \sum_{i=1}^{n} a_i \times Y^i$$

where Y is the perpendicular distance between the point of the aspherical surface and the optical axis, Z(Y) is the depth of the aspheric surface of the lens element (the height of a point on the aspheric surface at a distance Y from the optical axis relative to the tangential plane at the aspheric surface vertex), R is the radius of curvature in millimeters (mm) from the optical axis to the lens surface, K is a conic constant, and a(i) is an aspheric surface coefficient of i-th level (or order term).

Table 1B shows numeric lens data of the conic constant K and aspheric surface coefficients as for each of the lens surfaces of optical lens system **100** according to the first embodiment of the present invention. All three lens elements are made of the plastic material F52R.

TABLE 1B

Surface #	Semi-diameter	K	2nd order term	4th order term	6th order term	8th order term
R1	0.580299398	0	0	−0.067839721	0.044054737	−0.762442363
R2	0.642096093	0	0	−0.180210174	−0.755286781	1.110817088
R3	0.635116852	0	0	−0.170304259	−1.774214489	10.65840905
R4	0.785121131	1.097413	0	−0.123411613	1.169170197	−2.025499469
R5	1.268930266	−0.65339	0	−1.112804329	1.164130931	−0.789364157
R6	1.489447156	−3.58075	0	−0.534342342	0.635678424	−0.53439723

Surface #	10th order term	12th order term	14th order term	16th order term
R1	1.398532503	−9.682710644	35.71081656	−55.82129617
R2	−1.677479594	−1.557681967	0	
R3	−23.70906044	26.70690794	−16.200458	
R4	5.905125575	−6.30895851	3.199135509	
R5	0.259769069	0.006464826	−0.016099134	
R6	0.275980253	−0.080064437	0.009235139	0.000289327

FIGS. **2**B and **2**C are graphs illustrating the respective astigmatic field curvatures and distortion for a wavelength of 940 nm in optical lens system **100** of FIG. **2**A. The sagittal (denoted "S") and tangential (denoted "T") astigmatic curvatures are less than ±0.10 mm and the distortion is less than +2.0 percent.

Second Embodiment

Table 2A shows numeric lens data of the lens elements of optical lens system **100** according to a second embodiment of the present invention. All three lens elements are made of the polycarbonate plastic material SP3810.

TABLE 2A

	Curvature Radius (1/mm)	Radius (mm)	Thickness/air gap (mm)	Refractive index	Abbe #	material
Object		Infinity	14400			
Aperture stop		Infinity	−0.1275			
Lens 1	8.40E−01	1.190429	0.51	1.639753	23.35202	SP3810
	8.69E−02	11.50411	0.25357			
Lens 2	−7.97E−01	−1.25471	0.524634	1.639753	23.35202	SP3810
	−6.66E−01	−1.50217	0.572298			
Lens 3	7.85E−01	1.274121	0.35	1.639753	23.35202	SP3810
	1.16E+00	0.859237	0.36			
filter	Infinity		0.21	1.52	64.2	
	Infinity		0.3			
Image plane	Infinity		0			

In the second embodiment, the effective focal length (EFL) is 2.5631 mm, the half field of view (HFOV) is 36.1 degrees. The F number is 2.19. The image height is 1.87 mm. The BFL is 0.87 mm. The entire length of the optical system **100** measured from the object-side surface of the first lens element to the image plane is 3.081 mm. The angular magnification is 1.317. The diameter of the aperture stop is 1.16 mm. The diameter of the filter is 3.375 mm.

Table 2B shows numeric lens data of the conic constant K and aspheric surface coefficients as for each of the lens surfaces of optical lens system **100** according to the second embodiment of the present invention. All three elements are made of the polycarbonate plastic material SP3810.

TABLE 2B

Surface #	Semi-diameter	K	2nd order term	4th order term	6th order term	8th order term
R1	0.590114194	0	0.00E+00	−5.40E−02	2.94E−02	−6.62E−01
R2	0.645377793	0	0.00E+00	−2.05E−01	−8.69E−01	1.55E+00
R3	0.626322157	0	0.00E+00	−2.57E−01	−1.43E+00	1.01E+01
R4	0.760416577	2.402905	0.00E+00	−1.52E−01	1.41E+00	−2.79E+00
R5	1.268108848	−0.62102	0.00E+00	−9.82E−01	9.59E−01	−6.71E−01
R6	1.464402246	−4.03413	0.00E+00	−5.11E−01	5.91E−01	−5.08E−01

Surface #	10th order term	12th order term	14th order term	16th order term
R1	1.39E+00	−1.01E+01	3.76E+01	−5.78E+01
R2	−3.56E+00	1.05E+00		
R3	−2.97E+01	4.70E+01	−3.53E+01	
R4	6.42E+00	−5.40E+00	2.34E+00	
R5	2.46E−01	−6.59E−03	−1.21E−02	
R6	2.71E−01	−8.23E−02	1.05E−02	1.79E−04

In one embodiment, the three lens elements L**1**, L**2**, and L**3** are made of the same plastic material that is capable of absorbing visible light. In other words, light with a wavelength below 900 nm will not be able to pass through the lens elements. In one embodiment, the three lens elements have the same refractive index of about 1.53 and an Abbe number of about 55.6. In another embodiment, the three lens elements have the same refractive index of about 1.63 and an Abbe number of about 23.35.

Four-Element Lens System

Third Embodiment

FIG. **3**A is a simplified cross sectional view of a four-element optical lens system **200** according to an embodiment of the present invention. Optical lens system **200** includes an aperture stop AS, a first lens element L**1**, a second lens element L**2**, a third lens element L**3**, and a fourth lens element L**4**, in order from the object side to the image side along the optical axis. Each lens element L**1**-L**4** can be rotationally symmetric above the optical axis.

First lens element L**1** has a positive refractive power, a convex object-side surface, a convex image-side surface in the outer circumferential region, and a concave image-side surface in the vicinity of the optical axis. Second lens element L**2** has a negative refractive power, a concave object-side surface in the vicinity of the optical axis, a concave object-side surface in the outer circumferential region, a concave image-side surface in the outer circumferential region, and a concave image side surface in the vicinity of the optical axis. Third lens element L**3** has a positive refractive power, a concave object-side along the optical axis, a concave object-side surface in the outer circumferential region, a convex image-side surface in the outer circumferential region, and a convex surface on the image side along the optical axis. Fourth lens element L**4** has a negative refractive power, a convex object-side surface in the vicinity of the optical axis, a convex object-side surface

in the outer circumferential region, and a concave image side surface in the vicinity of the optical axis and a convex image-side surface in the outer circumferential region.

Optical lens system **200** also includes a filter configured to block the passage of light at visible wavelengths. In some embodiments, the filter filters out wavelengths below about 700 nm. The optical filter blocks shorter wavelengths of the visible spectrum and passes through wavelengths above about 700 nm. The filter improves the infrared performance of the imaging lens system **200** by reducing interference from other light sources. Although the filter is shown as a single filter disposed between the third lens element and the image plane, the filter can be disposed in any other locations and can have one or more filter elements.

As shown in FIG. **3**A, R**1** and R**2** are the respective object side and image side surface of first lens element L**1**. R**3** and R**4** are the respective object side and image side surface of second lens element L**2**. Similarly, R**5** and R**6** are the respective object-side and image-side surface of third lens element L**3**. Likewise, R**7** and R**8** are the respective object-side and image-side surface of fourth lens element L**4**.

In one embodiment, lens elements L**1**, L**2**, L**3**, and L**4** each are made of the same material, which passes near infrared light having a wavelength about 900 nm. In another embodiment, the material of the lens elements L**1**, L**2**, L**3**, and L**4** has a high absorption for visible light and a high transmission for near infrared light longer than 900 nm, preferably at 940 nm.

Referring to FIG. **3**A, T**1** is the thickness of first lens element L**1**, T**2** is the thickness of the second lens element L**2**, T**3** is the thickness of the third lens element L**3**, and T**4** is the thickness of the fourth lens element L**4**. Thicknesses T**1**-T**4** are each measured along the optical axis. AC**12** is the air gap between the first and second lens elements, AC**23** is the air gap between the second and third lens elements, and AC**34** is the air gap between the third and fourth lens elements. Air gaps AC**12**, AC**23**, and AC**34** are each measured along the optical axis. BFL denotes the back focal length, which is the distance between the image side of the fourth lens element and the image plane along the optical axis. BFL includes the thickness of the optical filter if the filter is disposed between the fourth lens element and the image plane. EFL denotes the effective focal length, which is also known as focal length.

In the following sections, ALT denotes the total thickness of the first to fourth lens elements, i.e., ALT=T**1**+T**2**+T**3**+T**4**. AAG denotes the total width of the air gaps of the first to fourth lens elements along the optical axis, i.e., AAG=AC**12**+AC**23**+AC**34**.

According to certain embodiments of the present invention, in order to reduce the total length of the optical lens system, the following measures can be taken: reducing the thickness of the lens elements and the air gaps between them. However, it is difficult to reduce the total thickness of the lens elements while maintaining adequate optical performance. Accordingly, the first lens element is designed to have a positive refractive power, the second lens element is designed to have a negative refractive power, the third lens element is designed to have a negative refractive power, and the fourth lens element is designed to have a positive refractive power. In order to increase the production yield and reduce manufacturing costs all fourth lens elements can be made of the same material. In one embodiment, the optical lens material has an absorption spectrum of visible light in the range from 400 nm to 700 nm, while having high transmission for wavelengths above 850 nm.

In one embodiment, all fourth lens elements L**1**, L**2**, L**3**, and L**4** can be made of the same plastic material and coated with an antireflective material optimized for near-infrared radiation. In a preferred embodiment, the antireflective material has a transmission peak at about 940 nm.

Table 3A shows numeric lens data of the lens elements of optical lens system **200** according to an embodiment of the present invention. All four lens elements are made of the same plastic material to simplify the manufacturing process and reduce the manufacturing costs.

TABLE 3A

	Curvature Radius (1/mm)	Radius (mm)	Thickness/air gap (mm)	Refractive index	Abbe #	material
Object		Infinity	10000			
Aperture stop		Infinity	−0.12476			
Lens 1	9.12E−01	1.096272	0.489626	1.5441	55.8	plastic
	1.06E−01	9.392786	0.114955			
Lens 2	−1.85E−01	−5.3966	0.24	1.5441	55.8	plastic
	3.23E−02	30.94121	0.304479			
Lens 3	−8.37E−01	−1.19525	0.455357	1.5441	55.8	plastic
	−1.62E+00	−0.6169	0.136123			
Lens 4	3.47E−01	2.878439	0.309657	1.5441	55.8	plastic
	1.40E+00	0.713182	0.514822			
filter	Infinity		0.21	1.52	64.2	
	Infinity		0.3			
Image plane	Infinity		0			

In this embodiment, the effective focal length (EFL) is 2.4818 mm, the half field of view (HFOV) is 37.08 degrees. The F number is 2.199. The image height is 1.876 mm. The BFL is 1.025 mm. The total length from the object-side surface of the first lens element to the image plane is 3.075 mm. The angular magnification is 1.151. The diameter of the aperture stop is 1.12 mm. The diameter of the filter is 3.361 mm.

Table 3B shows numeric values of the conic constant K and aspheric surface coefficients for each of the aspheric lens surfaces of the four lens elements.

TABLE 3B

Surface #	Semi-diameter	K	2nd order term	4th order term	6th order term	8th order term
R1	0.583316716	0		−7.49E−02	4.45E−01	−2.53E+00
R2	0.631494381	0		−2.57E−01	−5.99E−01	−3.33E+00
R3	0.626133161	0		−2.48E−01	−1.72E+00	2.75E+00
R4	0.661635554	0		3.88E−02	4.13E−01	−4.23E+00
R5	0.686552237	0		1.59E−01	−5.61E−01	2.47E−01
R6	0.848811908	−0.77041		8.59E−01	−2.08E+00	4.19E+00
R7	1.205435147	3.352184		−4.83E−01	1.39E−01	3.60E−01
R8	1.432267496	−5.69912		−3.51E−01	3.56E−01	−2.96E−01

Surface #	10th order term	12th order term	14th order term	16th order term
R1	4.22E+00	2.12E−01	−1.32E+01	
R2	1.32E+01	−2.25E+01	1.56E+01	
R3	−8.25E−01	3.75E+00		
R4	1.92E+01	−3.45E+01	2.64E+01	
R5	1.68E+00	−9.22E−01	−2.76E+00	
R6	−5.20E+00	5.27E+00	−2.48E+00	
R7	−5.23E−01	2.85E−01	−5.68E−02	
R8	1.55E−01	−4.56E−02	4.41E−03	4.71E−04

FIGS. **3**B and **3**C are graphs illustrating the respective astigmatic field curvatures and distortion for a wavelength of 940 nm in optical lens system **200** of FIG. **3**A. The sagittal (denoted "S") and tangential (denoted "T") astigmatic curvature are less than ±0.06 mm and the distortion is less than ±2.0 percent.

Four Lens Element Telecentric Lens System **300**

Fourth Embodiment

FIG. **4** is a simplified cross sectional view of a four-element optical lens system **300** according to an embodiment of the present invention. Optical lens system **300** is a telecentric lens system including a first lens element L**1**, a second lens element L**2**, a third lens element L**3**, and a fourth lens element L**4**, arranged in order from the object side to the image side along the optical axis. Each lens element L**1**-L**4** can be rotationally symmetric above the optical axis. In an embodiment, optical lens system **300** further includes an aperture stop AS disposed between the first lens element L**1** and the second lens element L**2**.

First lens element L**1** has a positive refractive power, a planar object-side surface, a convex image-side surface in the outer circumferential region, and a convex image-side surface in the vicinity of the optical axis. Second lens element L**2** has a negative refractive power, a convex object-side surface in the vicinity of the optical axis, a convex object-side surface in the outer circumferential region, a concave image-side surface in the outer circumferential region, and a concave image side surface in the vicinity of the optical axis. Third lens element L**3** has a negative refractive power, a concave object-side along the optical axis, a concave object-side surface in the outer circumferential region, a convex image-side surface in the outer circumferential region, and a convex surface on the image side along the optical axis. Fourth lens element L**4** has a positive refractive power, a convex object-side surface in the vicinity of the optical axis, a convex object-side surface in the outer circumferential region, a convex image-side surface in the outer circumferential region, and a convex image side surface in the vicinity of the optical axis.

As shown in FIGS. **4**, R**1** and R**2** are the respective object side and image side surface of first lens element L**1**. R**3** and R**4** are the respective object side and image side surface of second lens element L**2**. Similarly, R**5** and R**6** are the respective object-side and image-side surface of third lens element L**3**. Likewise, R**7** and R**8** are the respective object-side and image-side surface of fourth lens element L**4**.

In one embodiment, lens elements L**1**, L**2**, L**3**, and L**4** each are made of the same material, which passes near infrared light having a wavelength about 900 nm and have a high absorption for visible light. In a specific embodiment, the material of lens elements L**1**, L**2**, L**3**, and L**4** has a transmission peak at 940 nm.

Referring to FIG. **4**, T**1** is the thickness of first lens element L**1**, T**2** is the thickness of the second lens element L**2**, T**3** is the thickness of the third lens element L**3**, and T**4** is the thickness of the fourth lens element L**4**. Thicknesses T**1**-T**4** are each measured along the optical axis. AC**12** is the air gap between the first and second lens elements, AC**23** is the air gap between the second and third lens elements, and AC**34** is the air gap between the third and fourth lens elements. Air gaps AC**12**, AC**23**, and AC**34** are each measured along the optical axis. BFL denotes the back focal length, which is the distance between the image side of the fourth lens element and the image plane along the optical axis. BFL includes the thickness of the optical filter if the filter is disposed between the fourth lens element and the image plane. EFL denotes the effective focal length, which is also known as focal length.

In the following sections, ALT denotes the total thickness of the first to fourth lens elements, i.e., ALT=T**1**+T**2**+T**3**+T**4**. AAG denotes the total width of the air gaps of the first to fourth lens elements along the optical axis, i.e., AAG=AC**12**+AC**23**+AC**34**.

According to certain embodiments of the present invention, in order to reduce the total length of the optical lens system, the following measures can be taken: reducing the thickness of the lens elements and the air gaps between them. However, it is difficult to reduce the total thickness of the lens elements while maintaining adequate optical performance. Accordingly, the first lens element is designed to have a positive refractive power, the second lens element is designed to have a negative refractive power, the third lens element is designed to have a negative refractive power, and the fourth lens element is designed to have a positive refractive power. The air gap between the first and second lens elements is about 0.02 mm. The air gap between the second and third lens elements is about 0.196 mm. The air gap between the third and fourth lens elements is about 0.05 mm.

In one embodiment, all fourth lens elements L1, L2, L3, and L4 can be made of the same plastic material and coated with an antireflective material optimized for near-infrared radiation. In a preferred embodiment, the antireflective material has a transmission peak at about 940 nm.

Table 4A shows numeric lens data of the lens elements of optical lens system **300** according to an embodiment of the present invention. All four lens elements are made of the same plastic material to simplify the manufacturing process and reduce the manufacturing costs.

TABLE 4A

	Curvature Radius (1/mm)	Radius (mm)	Thickness/air gap (mm)	Refractive index	Abbe #
Object		Infinity	10000		
Lens 1		Infinity	0.35	1.639753	23.35202
	−9.77E−01	−1.02391	0.02		
Lens 2	1.65E+00	0.604434	0.3	1.639753	23.35202
	2.72E+00	0.367997	0.195861		
Lens 3	−1.89E+00	−0.52892	0.3	1.639753	23.35202
	−1.31E+00	−0.76577	0.05		
Lens 4	1.31E+00	0.76423	0.5	1.639753	23.35202
	−7.10E−01	−1.40872	0.4		

In this embodiment, the effective focal length (EFL) is 1.0588 mm, the half field of view (HFOV) is 18.11 degrees. The F number is 2.07. The image height is 0.346 mm. The BFL is 0.398 mm. The total length from the object-side surface of the first lens element to the image plane is about 2.116 mm. The angular magnification is 0.0622. The diameter of the aperture stop is about 0.498 mm and the thickness is 0.02 mm. All four lens elements are made of the same high quality material having an index of refraction of 1.6397. The chief ray angle is smaller than 1 degree across the field.

Table 4B shows numeric values of the conic constant K and aspheric surface coefficients for each of the aspheric lens surfaces of the four lens elements.

TABLE 4B

Surface #	Semi-diameter	K	2nd order term	4th order term	6th order term	8th order term
R1	0.338471742	0				
R2	0.276312851	0		1.19E+00	−4.80E+00	1.36E+01
R3	0.26533854	0		2.08E−01		
R4	0.241014398	0		−3.58E+00		
R5	0.258098858	0		2.80E−02		
R6	0.371279568	0		3.64E−02		
R7	0.469899148	0		−3.73E−01	3.84E−02	
R8	0.451692498	0		5.29E−01	−4.75E−01	2.67E−01

All order terms higher than the 8th order term are zeros. The conic constant is zero for all even aspheric surface of the four lens elements.

Four Lens Element Telecentric Lens System **400**

Fifth Embodiment

FIG. **5**A is a simplified cross-sectional view of a four-element optical lens system **400** according to an embodiment of the present invention. Optical lens system **400** is a telecentric lens system including a first lens element L1, a second lens element L2, a third lens element L3, and a fourth lens element L4, arranged in order from the object side to the image side along the optical axis. Each lens element L1-L4 can be rotationally symmetric above the optical axis.

First lens element L1 has a positive refractive power, a convex object-side surface in the vicinity of the optical axis, a convex object-side surface in the outer circumferential region, a convex image-side surface in the vicinity of the optical axis, and a convex image-side surface in the outer circumferential region. Second lens element L2 has a negative refractive power, a convex object-side surface in the vicinity of the optical axis, a convex object-side surface in the outer circumferential region, a concave image-side surface in the vicinity of the optical axis, and a concave image side surface in the outer circumferential region. Third lens element L3 has a negative refractive power, a concave object-side in the vicinity of the optical axis, a concave object-side surface in the outer circumferential region, a concave image-side surface in the vicinity of the optical axis, and a concave surface in the outer circumferential region. Fourth lens element L4 has a positive refractive power, a convex object-side surface in the vicinity of the optical axis, a convex object-side surface in the outer circumferential region, a convex image-side surface in the vicinity of the optical axis, and a convex image-side surface in the outer circumferential region.

Optical lens system **400** further includes an aperture stop AS disposed in front of the first lens element L1, where the optical axis intersects the center of the aperture stop.

Referring to FIGS. **5**, R1 and R2 are the respective object side and image side surface of first lens element L1. R3 and R4 are the respective object side and image side surface of second lens element L2. Similarly, R5 and R6 are the respective object-side and image-side surface of third lens element L3. Likewise, R7 and R8 are the respective object-side and image-side surface of fourth lens element L4.

In one embodiment, lens elements L1, L2, L3, and L4 each are made of the same material, which passes near infrared light having a wavelength about 900 nm and have a high absorption for visible light. In a specific embodiment, the material of lens elements L1, L2, L3, and L4 has a transmission peak at 940 nm. In some embodiments, lens elements may be made of Ultem 1010, Ultem XH6050, Extem XH1005, and Extem UH1006.

Still referring to FIG. **4**, T1 is the thickness of first lens element L1, T2 is the thickness of the second lens element

L2, T3 is the thickness of the third lens element L3, and T4 is the thickness of the fourth lens element L4. Thicknesses T1-T4 are each measured along the optical axis. AC12 is the air gap between the first and second lens elements, AC23 is the air gap between the second and third lens elements, and AC34 is the air gap between the third and fourth lens elements. Air gaps AC12, AC23, and AC34 are each measured along the optical axis. BFL denotes the back focal length, which is the distance between the image side of the fourth lens element and the image plane along the optical axis. BFL includes the thickness of the optical filter if the filter is disposed between the fourth lens element and the image plane. EFL denotes the effective focal length, which is also known as focal length.

In the following sections, ALT denotes the total thickness of the first to fourth lens elements, i.e., ALT=T1+T2+T3+T4. AAG denotes the total width of the air gaps of the first to fourth lens elements along the optical axis, i.e., AAG=AC12+AC23+AC34.

Table 5A shows numeric lens data of the lens elements of optical lens system **400** according to an embodiment of the present invention. All four lens elements are made of the same plastic material to simplify the manufacturing process and reduce the manufacturing costs.

TABLE 5A

	Curvature Radius (1/mm)	Radius (mm)	Thickness/air gap (mm)	Refractive index	Abbe #
Object		Infinity	1E+08		
Aperture stop		Infinity	−0.3176		
Lens 1	9.50E−01	1.052815	0.52	1.639753	23.35202
	−2.00E−02	−50.0992	0.04		
Lens 2	1.12E+00	0.89579	0.32	1.639753	23.35202
	1.95E+00	0.513552	0.801427		
Lens 3	−8.36E−01	−1.19688	0.28	1.639753	23.35202
	2.24E+00	0.445971	0.184473		
Lens 4	9.80E−01	1.020037	0.4	1.639753	23.35202
	−1.60E+00	−0.62529	0.1		

In this embodiment, the effective focal length (EFL) is 3.614 mm, the half field of view (HFOV) is 4.896 degrees. The F number is 2.3. The image height is 0.3096 mm. The BFL is 0.1 mm. The total length from the object-side surface of the first lens element to the image plane is about 2.678 mm. The angular magnification is −0.3587. The diameter of the aperture stop is about 1.57 mm and the thickness of is 0.35 mm. All four lens elements are made of the same high quality material having an index of refraction of 1.6397.

According to this embodiment, the air gap between the first and second lens elements is about 0.04 mm, the air gap between the second and third lens elements is about 0.80 mm, and the air gap between the third and fourth lens elements is about 0.18 mm.

Table 5B shows numeric values of the conic constant K and aspheric surface coefficients for each of the aspheric lens surfaces of the four lens elements.

TABLE 5B

Surface #	Semi-diameter	K	2nd order term	4th order term	6th order term	8th order term	10th order term
R1	0.338471742	0.009547		−3.09E−02	−1.23E−01	1.20E−01	−1.35E−01
R2	0.276312851	0					
R3	0.26533854	−0.38324					
R4	0.241014398	−0.17923					
R5	0.258098858	3.536838					
R6	0.371279568	0		7.22E−01			
R7	0.469899148	0		−1.04E+00			
R8	0.451692498	0		4.08E−01	−1.76E+00		

All order terms higher than the 10th order term are zeros.

FIG. **5**B is a MTF graph for the optical lens system **400**.

Various materials having an absorption spectrum of visible light and high transmission for near infrared wavelengths are known. For example, Ultem XH6050, Extem XH1005, Extem UH1006 are suitable materials for making lens elements of the present disclosure.

Sixth Embodiment

FIG. **6**A is a simplified cross-section view of a four-element optical lens system **500** according to a sixth embodiment of the present invention. Optical lens system **500** comprises a first lens element L**11**, a second lens element L**12**, a third lens element L**13**, and a fourth lens element L**14**, arranged in order from the object side to the image side along the optical axis. Each lens element L**11**-L**14** can be rotationally symmetric above the optical axis.

First lens element L**11** has a positive refractive power, a convex object-side surface in the vicinity of the optical axis, a convex object-side surface in the outer circumferential region, and a concave image-side surface in the vicinity of the optical axis. Second lens element L**12** has a negative refractive power, a convex object-side surface in the vicinity of the optical axis, a convex object-side surface in the outer circumferential region, a concave image-side surface in the vicinity of the optical axis, and a concave image side surface in the outer circumferential region. Third lens element L**13** has a negative refractive power, a concave object-side in the vicinity of the optical axis, a concave object-side surface in the outer circumferential region, a concave image-side surface in the vicinity of the optical axis, and a concave surface in the outer circumferential region. Fourth lens element L**14** has a positive refractive power, a concave object-side surface in the vicinity of the optical axis, a concave object-side surface in the outer circumferential region, a convex image-side surface in the vicinity of the optical axis, and a convex image-side surface in the outer circumferential region.

Optical lens system **500** further includes a filter F**11** disposed between fourth lens element L**14** and an imaging sensor. In an embodiment, filter F**11** may be made of glass.

TABLE 6A

	Curvature Radius (1/mm)	Radius (mm)	Thickness/air gap (mm)	Refractive index	Abbe #
Object		Infinity	1E+08		
Lens 11	1.32E+00	7.60E−01	T1 = 6.08E−01	1.639753	23.35202
	1.51E−01	6.61E+00	AC1S = 8.00E−02		
			ACS2 = 2.00E−02		
Lens 12	8.32E−01	1.20E+00	T2 = 2.82E−01	1.639753	23.35202
	1.76E+00	5.67E−01	AC23 = 2.74E−01		
Lens 13	−1.09E+00	−9.21E−01	T3 = 2.81E−01	1.639753	23.35202
	1.90E+00	5.25E−01	AC34 = 2.37E−01		
Lens 14	−6.75E−03	−1.48E+02	T4 = 4.19E−01	1.639753	23.35202
	−1.27E+00	−7.89E−01	AC4F = 1.00E−01		
filter	0.00E+00		TF = 3.00E−01	1.5168	64.16
Image plane			ACFP = 1.00E−01		

Optical lens system **500** further includes an aperture stop AS disposed between first lens element L**11** and second lens element L**12**, where the optical axis intersects the center of the aperture stop.

Referring to FIG. **6**A, R**1** and R**2** are the respective object side and image side surface of first lens element L**11**. R**3** and R**4** are the respective object side and image side surface of second lens element L**12**. Similarly, R**5** and R**6** are the respective object-side and image-side surface of third lens element L**13**. Likewise, R**7** and R**8** are the respective object-side and image-side surface of fourth lens element L**14**.

In one embodiment, lens elements L**11**, L**12**, L**13**, and L**14** each are made of the same material, which passes near infrared light having a wavelength about 900 nm and have a high absorption for visible light. In a specific embodiment, the material of lens elements L**11**, L**12**, L**13**, and L**14** has a transmission peak at 940 nm. In some embodiments, lens elements may be made of Ultem 1010, Ultem XH6050, Extem XH1005, and Extem UH1006.

Still referring to FIG. **6**A, T**1** is the thickness of first lens element L**11**, T**2** is the thickness of the second lens element L**12**, T**3** is the thickness of the third lens element L**13**, and T**4** is the thickness of the fourth lens element L**14**. Thicknesses T**1**-T**4** are each measured along the optical axis. AC**12** is the air gap between the first and second lens elements and includes the distance AC**1**S between the image-side surface of first lens L**11** and the center of the aperture stop AS and the distance ACS**2** between the center of the aperture stop AS and the object-side surface of second lens element L**12**. AC**23** is the air gap between the second and third lens elements, and AC**34** is the air gap between the third and fourth lens elements. Air gaps AC**12**, AC**23**, and AC**34** are each measured along the optical axis. BFL denotes the back focal length, which is the distance between the image side of the fourth lens element and the image plane along the optical axis. BFL includes the thickness of the optical filter if the filter is disposed between the fourth lens element and the image plane. EFL denotes the effective focal length, which is also known as focal length.

In the following sections, ALT denotes the total thickness of the first to fourth lens elements, i.e., ALT=T**1**+T**2**+T**3**+T**4**. AAG denotes the total width of the air gaps of the first to fourth lens elements along the optical axis, i.e., AAG=AC**12**+AC**23**+AC**34**.

Table 6A shows numeric lens data of the lens elements of optical lens system **500** according to an embodiment of the present invention. All four lens elements are made of the same plastic material to simplify the manufacturing process and reduce the manufacturing costs.

In this embodiment, the effective focal length (EFL) is 3.7999 mm, the half field of view (HFOV) is 5.387 degrees. The F number is 2.3. The image height is 0.358 mm. The BFL is 0.5 mm. The total length from the object-side surface of the first lens element to the image plane is about 2.701 mm. The angular magnification is 1.422. The diameter of the aperture stop is about 1.05 mm. All four lens elements are made of the same high quality material having an index of refraction of 1.6397.

According to this embodiment, the air gap AC**12** between the first and second lens elements is the sum of the air gap AC**1**S and ACS**2** and is about 0.1 mm, where AC**1**S is the distance between the image-side surface of first lens element L**11** and the aperture stop AS, and ACS**2** is the distance between the aperture stop AS and the object-side surface of second lens element L**12** along the optic axis. The air gap AC**23** between the second and third lens elements is about 0.274 mm, and the air gap between the third and fourth lens elements is about 0.237 mm along the optical axis. The filter may be made of glass and has a thickness of about 0.3 mm. The filter has a refractive index of 1.5168 and an Abbe number of 64.16. The filter is disposed at about 0.1 mm from the image-side of fourth lens element L**14** and 0.1 mm from the image plane along the optical axis. The telephoto ratio is about 0.71058. In an embodiment, the sum of all air gaps AAG between the first through the fourth lens elements is 0.611. The ratio of AAG/T**3** is 2.174.

According to certain embodiments of the present invention, in order to reduce the total length of the optical lens system, the following measures can be taken: reducing the thickness of the lens elements and the air gaps between them. However, it is difficult to reduce the total thickness of the lens elements while maintaining adequate optical performance. Accordingly, the first lens element is designed to have a positive refractive power, the second lens element is designed to have a negative refractive power, and the third lens element is designed to have a positive refractive power. In order to increase the production yield and reduce manufacturing costs all three lens elements can be made of the same material. In one embodiment, the optical lens material has an absorption spectrum of visible light with a wavelength in the range between 400 nm and 700 nm, while having high transmission for wavelengths above 850 nm.

According to the first embodiment, all four lens elements L**11**, L**12**, L**13**, and L**14** can be made of the same material and coated with an antireflective material optimized for near-infrared radiation. The first lens element has a positive

refractive power, a convex surface on the object-side in the vicinity of the optical axis, and a concave surface on the image-side in the vicinity of the optical axis. The second lens element has a negative refractive power, the third lens element has a concave surface on the object in the vicinity of the optical axis, and a concave surface near the outer circumference, and the fourth lens element has a convex image-side surface. The object-side and image-side surfaces of the four lens elements are even aspheric. The combination of these four lens elements provides the desired lens system quality. Making the four lens elements of the same material can lower the manufacturing costs and simplify the manufacturing process.

Table 6B shows numeric lens data of the conic constant K and aspheric surface coefficients as for each of the lens surfaces of optical lens system **100** according to the second embodiment of the present invention.

TABLE 6B

Surface #	Semi-diameter	K	2nd order term	4th order term	6th order term	8th order term	10th order term
R1	6.93E−01	−3.32E−01		1.88E−02	−8.85E−02	2.99E−01	−2.65E−01
R2	5.65E−01	0		8.43E−02	−5.34E−02	3.59E−03	
R3	4.53E−01	3.12E+00		3.19E−01	−8.40E−01		
R4	2.93E−01	1.67E+00		6.75E−01	4.41E+00		
R5	2.52E−01	8.23E+00		5.64E−01			
R6	2.51E−01	0		8.28E−03	−3.63E+00	2.60E+01	
R7	3.13E−01	0		−1.44E+00	2.44E−01		
R8	3.98E−01	0		−2.05E+00	6.47E+00	−2.27E+00	

All order terms higher than the 10th order term are zeros.

FIGS. **6**B-**6**O are a set of graphs illustrating the transverse ray fan plot of the optical imaging system **500** shown in FIG. **6**A. FIGS. **6**B and **6**C illustrate transverse ray fan plots for an object zero degrees off axis in the y-plane and the x-plane, respectively. FIGS. **6**D and **6**E illustrate transverse ray fan plots for an object one degree off axis in the y-plane and the x-plane, respectively. FIGS. **6**F and **6**G illustrate transverse ray fan plots for an object two degrees off axis in the y-plane and the x-plane, respectively. FIGS. **6**H and **6**I illustrate transverse ray fan plots for an object three and one half degrees off axis in the y-plane and the x-plane, respectively. FIGS. **6**J and **6**K illustrate transverse ray fan plots for an object four degrees off axis in the y-plane and the x-plane, respectively. FIGS. **6**L and **6**M illustrate transverse ray fan plots for an object four and one half degrees off axis in the y-plane and the x-plane, respectively. FIGS. **6**N and **6**O illustrate transverse ray fan plots for an object 5.387 degrees off axis in the y-plane and the x-plane, respectively.

Seventh Embodiment

FIG. **7**A is a simplified cross sectional view of a four-element optical lens system **600** according to an embodiment of the present invention. Optical lens system **600** includes, a first lens element L**21**, an aperture stop AS, a second lens element L**22**, a third lens element L**23**, and a fourth lens element L**24**, arranged in order from the object side to the image side along the optical axis. Each lens element L**21**-L**24** can be rotationally symmetric above the optical axis.

First lens element L**21** has a positive refractive power, a convex object-side surface, a convex image-side surface in the outer circumferential region, and a concave image-side surface in the vicinity of the optical axis. Second lens element L**22** has a negative refractive power, a convex object-side surface in the vicinity of the optical axis, and a concave image side surface in the vicinity of the optical axis. Third lens element L**23** has a negative refractive power, a concave object-side along the optical axis, and a concave surface on the image side along the optical axis. Fourth lens element L**24** has a positive refractive power, a convex object-side surface in the vicinity of the optical axis, and a convex image side surface in the vicinity of the optical axis and a convex image-side surface in the outer circumferential region.

Optical lens system **600** also includes a filter F**21** configured to block the passage of light at visible wavelengths. In some embodiments, the filter filters out wavelengths below about 700 nm. The optical filter blocks shorter wavelengths of the visible spectrum and passes through wavelengths above about 700 nm. The filter improves the infrared performance of the imaging lens system **600** by reducing interference from other light sources. Although filter F**21** is shown as a single filter disposed between the fourth lens element and the image plane, filter F**21** can be disposed in any other locations and can have one or more filter elements. Filter F**21** can be similar to filter F**11** described above.

As shown in FIG. **7**A, R**1** and R**2** are the respective object side and image side surface of first lens element L**21**. R**3** and R**4** are the respective object side and image side surface of second lens element L**22**. Similarly, R**5** and R**6** are the respective object-side and image-side surface of third lens element L**23**. Likewise, R**7** and R**8** are the respective object-side and image-side surface of fourth lens element L**24**.

In one embodiment, lens elements L**21**, L**22**, L**23**, and L**24** each are made of the same material, which passes near infrared light having a wavelength about 900 nm. In another embodiment, the material of the lens elements L**21**, L**22**, L**23**, and L**24** has a high absorption for visible light and a high transmission for near infrared light longer than 900 nm, preferably at 940 nm.

Referring to FIG. **7**A, T**1** is the thickness of first lens element L**21**, T**2** is the thickness of the second lens element L**22**, T**3** is the thickness of the third lens element L**23**, and T**4** is the thickness of the fourth lens element L**24**. Thicknesses T**1**-T**4** are each measured along the optical axis. AC**1**S is the distance between the first lens element and the aperture stop AS, ACS**2** is the distance between the aperture stop AS and the object-side surface of the second lens element, so that the sum of AC**1**A and ACA**2** is the air gap AC**12** between the first and second lens elements. AC**23** is the air gap between the second and third lens elements, and AC**34** is the air gap between the third and fourth lens elements. Air gaps AC**12**, AC**23**, and AC**34** are each measured along the optical axis. BFL denotes the back focal length, which is the distance between the image side of the fourth lens element and the image plane along the optical axis. BFL includes the thickness of the optical filter if the filter is disposed between the fourth lens element and the

image plane. EFL denotes the effective focal length, which is also known as focal length.

In the following sections, ALT denotes the total thickness of the first to fourth lens elements, i.e., ALT=T**1**+T**2**+T**3**+T**4**. AAG denotes the total width of the air gaps of the first to fourth lens elements along the optical axis, i.e., AAG=AC**12**+AC**23**+AC**34**. In an embodiment, AAG is 0.9308 mm. The ratio of AAG/T**3** is 3.324. The ratio of EFL/T**4** satisfies the relation of 7.0≤EFL/T**4**. The ratio of AC**34**/T**3** satisfies the relation 0.8≤AC**34**/T**3**.

According to certain embodiments of the present invention, in order to reduce the total length of the optical lens system, the following measures can be taken: reducing the thickness of the lens elements and the air gaps between them. However, it is difficult to reduce the total thickness of the lens elements while maintaining adequate optical performance. Accordingly, the first lens element is designed to have a positive refractive power, the second lens element is designed to have a positive refractive power, the third lens element is designed to have a negative refractive power, and the fourth lens element is designed to have a positive refractive power. In order to increase the production yield and reduce manufacturing costs all fourth lens elements can be made of the same material. In one embodiment, the optical lens material has an absorption spectrum of visible light in the range from 400 nm to 700 nm, while having high transmission for wavelengths above 850 nm.

In one embodiment, all fourth lens elements L**21**, L**22**, L**23**, and L**24** can be made of the same material and coated with an antireflective material optimized for near-infrared radiation. In a preferred embodiment, the antireflective material has a transmission peak at about 940 nm.

Table 7A shows numeric lens data of the lens elements of optical lens system **600** according to an embodiment of the present invention. All four lens elements are made of the same material to simplify the manufacturing process and reduce the manufacturing costs.

In this embodiment, the effective focal length (EFL) is 3.798 mm, the half field of view (HFOV) is 5.469 degrees. The F number is 2.2. The image height is 0.3636 mm. The BFL is 0.51 mm. The total length TTL from the object-side surface of the first lens element to the image plane is 2.7018 mm. The telephoto ratio is 0.71147. The angular magnification is 1.5316. The diameter of the aperture stop is 1.38 mm. The diameter of the filter is 0.75 mm.

Table 7B shows numeric values of the conic constant K and aspheric surface coefficients for each of the aspheric lens surfaces of the four lens elements.

TABLE 7B

Surface #	Semi-diameter	K	2nd order term	4th order term	6th order term	8th order term	10th order term
R1	7.51E−01	1.46E−03		−3.02E−02	−2.91E−01	2.73E−01	−3.98E−01
R2	7.03E−01	0.00E+00		1.11E−01	−3.06E−02		
R3	6.21E−01	3.47E+00		1.99E−02	3.78E−01	5.58E−03	
R4	4.69E−01	−9.10E−01		3.01E−01	1.49E−01		
R5	2.92E−01	−2.85E+01		−3.34E+00	−3.11E+00		
R6	2.88E−01	0.00E+00		6.75E+00	−5.32E+01		
R7	3.99E−01	0.00E+00		1.34E+00	8.28E+00	−1.60E+01	
R8	3.89E−01	0.00E+00		−1.45E+00	1.48E+01	3.31E+00	

All order terms higher than the 10th order term are zeros.

FIGS. **7**B-**7**O are a set of graphs illustrating the transverse ray fan plot of the optical imaging system **600** shown in FIG. **7**A. FIGS. **7**B and **7**C illustrate transverse ray fan plots for an object zero degrees off axis in the y-plane and the x-plane, respectively. FIGS. **7**D and **7**E illustrate transverse ray fan plots for an object one degree off axis in the y-plane and the x-plane, respectively. FIGS. **7**F and **7**G illustrate transverse ray fan plots for an object two degrees off axis in the y-plane and the x-plane, respectively. FIGS. **7**H and **71** illustrate transverse ray fan plots for an object three and one half degrees off axis in the y-plane and the x-plane, respectively. FIGS. **7**J and **7**K illustrate transverse ray fan plots for an object four degrees off axis in the y-plane and the x-plane, respectively. FIGS. **7**L and **7**M illustrate transverse ray fan plots for an object four and one half degrees off axis in the y-plane and the x-plane, respectively. FIGS. **7**N and **7**O illustrate transverse ray fan plots for an object 5.4697 degrees off axis in the y-plane and the x-plane, respectively. FIG. **7**P is graph illustrating the modulus of the optical transfer function as a function of the spatial frequency (cycles/mm) in the embodiment of FIG. **7**A.

TABLE 7A

	Curvature Radius (1/mm)	Radius (mm)	Thickness/air gap (mm)	Refractive index	Abbe #
Object		Infinity	10000		
Lens 1	1.08E+00	9.26E−01	T1 = 0.46	1.639753	23.35202
	−1.17E−01	−8.56E+00	AC1S = 0.014829		
	0.00E+00		ACS2 = 0.02		
Lens 2	5.36E−01	1.87E+00	T2 = 0.300369	1.639753	23.35202
	1.13E+00	8.87E−01	AC23 = 0.615285		
Lens 3	−1.33E+00	−7.51E−01	T3 = 0.28	1.639753	23.35202
	1.65E+00	6.06E−01	AC34 = 0.281892		
Lens 4	4.08E−01	2.45E+00	T4 = 0.231201	1.639753	23.35202
	−8.95E−01	−1.12E+00	AC4F = 0.1		
filter	0.00E+00		TF = 0.3	1.5168	64.16
	0.00E+00		ACFP = 0.1		
Image plane	0.00E+00		0		

Eighth Embodiment

FIG. **8**A is a simplified cross sectional view of a four-element optical lens system **700** according to an embodiment of the present invention. Optical lens system **700** includes, an aperture stop AS, a first lens element L**31**, a second lens element L**32**, a third lens element L**33**, and a fourth lens element L**34**, arranged in order from the object side to the image side along the optical axis. Each lens element L**31**-L**34** can be rotationally symmetric above the optical axis.

First lens element L**31** has a positive refractive power. The object side surface of first lens element L**31** has a convex portion in the vicinity of the optical axis and a convex portion in the outer circumferential region. The image-side surface of first lens element L**31** has a convex portion in the vicinity of the optical axis. Second lens element L**32** has a negative refractive power, a convex object-side surface in the vicinity of the optical axis, and a concave image side surface in the vicinity of the optical axis. Third lens element L**33** has a negative refractive power, a convex object-side along the optical axis, and a concave surface on the image side along the optical axis. Fourth lens element L**34** has a negative refractive power, a concave object-side surface in the vicinity of the optical axis, and a concave image side surface in the vicinity of the optical axis.

Optical lens system **700** also includes a filter F**31** configured to block the passage of light at visible wavelengths. In some embodiments, the filter filters out wavelengths below about 700 nm. The optical filter blocks shorter wavelengths of the visible spectrum and passes through wavelengths above about 700 nm. The filter improves the infrared performance of the imaging lens system **700** by reducing interference from other light sources. Although filter F**31** is shown as a single filter disposed between the fourth lens element and the image plane, filter F**31** can be disposed in any other locations and can have one or more filter elements. Filter F**31** can be similar to filter F**11** of filter F**21** described above.

As shown in FIG. **8**A, R**1** and R**2** are the respective object side and image side surface of first lens element L**31**. R**3** and R**4** are the respective object side and image side surface of second lens element L**32**. Similarly, R**5** and R**6** are the respective object-side and image-side surface of third lens element L**33**. Likewise, R**7** and R**8** are the respective object-side and image-side surface of fourth lens element L**34**.

In one embodiment, lens elements L**31**, L**32**, L**33**, and L**34** each are made of the same material, which passes near infrared light having a wavelength about 900 nm. In another embodiment, the material of the lens elements L**31**, L**32**, L**33**, and L**34** has a high absorption for visible light and a high transmission for near infrared light longer than 900 nm, preferably at 940 nm.

Referring to FIG. **8**A, T**1** is the thickness of first lens element L**31**, T**2** is the thickness of the second lens element L**32**, T**3** is the thickness of the third lens element L**33**, and T**4** is the thickness of the fourth lens element L**34**. Thicknesses T**1**-T**4** are each measured along the optical axis. AC**12** is the air gap between the first and second lens elements, AC**23** is the air gap between the second and third lens elements, and AC**34** is the air gap between the third and fourth lens elements. Air gaps AC**12**, AC**23**, and AC**34** are each measured along the optical axis. BFL denotes the back focal length, which is the distance between the image side of the fourth lens element and the image plane along the optical axis. BFL includes the thickness of the optical filter if the filter is disposed between the fourth lens element and the image plane. EFL denotes the effective focal length, which is also known as focal length.

In the following sections, ALT denotes the total thickness of the first to fourth lens elements, i.e., ALT=T**1**+T**2**+T**3**+T**4**. AAG denotes the total width of the air gaps of the first to fourth lens elements along the optical axis, i.e., AAG=AC**12**+AC**23**+AC**34**.

According to certain embodiments of the present invention, in order to reduce the total length of the optical lens system, the following measures can be taken: reducing the thickness of the lens elements and the air gaps between them. However, it is difficult to reduce the total thickness of the lens elements while maintaining adequate optical performance. Accordingly, the first lens element is designed to have a positive refractive power, the second lens element is designed to have a positive refractive power, the third lens element is designed to have a negative refractive power, and the fourth lens element is designed to have a positive refractive power. In order to increase the production yield and reduce manufacturing costs all fourth lens elements can be made of the same material. In one embodiment, the optical lens material has an absorption spectrum of visible light in the range from 400 nm to 700 nm, while having high transmission for wavelengths above 850 nm.

In one embodiment, all fourth lens elements L**31**, L**32**, L**33**, and L**34** can be made of the same material and coated with an antireflective material optimized for near-infrared radiation. In a preferred embodiment, the antireflective material has a transmission peak at about 940 nm.

Table 8A shows numeric lens data of the lens elements of optical lens system **700** according to an embodiment of the present invention. All four lens elements are made of the same material to simplify the manufacturing process and reduce the manufacturing costs.

TABLE 8A

	Curvature Radius (1/mm)	Radius (mm)	Thickness/air gap (mm)	Refractive index	Abbe #
Object		Infinity	10000		
Aperture stop	0.00E+00		−3.17E−01		
Lens 1	9.20E−01	1.09E+00	T1 = 5.86E−01	1.639753	23.35202
	−9.92E−02	−1.01E+01	AC12 = 5.00E−02		
Lens 2	5.92E−01	1.69E+00	T2 = 3.15E−01	1.639753	23.35202
	8.72E−01	1.15E+00	AC23 = 3.82E−01		
Lens 3	5.93E−03	1.69E+02	T3 = 2.40E−01	1.639753	23.35202
	1.40E+00	7.16E−01	AC34 = 2.78E−01		
Lens 4	−6.88E−01	−1.45E+00	T4 = 2.40E−01	1.639753	23.35202
	5.28E−02	1.89E+01	AC4F = 1.00E−01		
filter	0.00E+00		TF = 2.10E−01	1.5168	64.16
	0.00E+00		ACFP = 3.00E−01		
Image plane	0.00E+00				

In this embodiment, the effective focal length (EFL) is 3.9999 mm, the half field of view (HFOV) is 5.3 degrees. The F number is 2.4. The image height is 0.3715 mm. The total length TTL from the object-side surface of the first lens element to the image plane is 2.703 mm. The telephoto ratio is 0.675. The angular magnification is 3.0447. The diameter of the aperture stop is 1.666 mm. The diameter of the filter is 0.678 mm. AAG is 0.71 mm. The ratio of AAG/T3 is greater than 2.0.

In this embodiment, the first lens element has a curvature radius R1 of 0.920 mm^{-1} and a curvature radius R2 of −0.0992 mm^{-1}. The second lens element has a curvature radius R3 of 0.592 mm^{-1} and a curvature radius R4 of −0.872 mm^{-1}. The third lens element has a curvature radius R5 of 0.00593 mm^{-1} and a curvature radius R6 of 1.40 mm^{-1}. The fourth lens element has a curvature radius R7 of −0.688 mm^{-1} and a curvature radius R8 of 0.0528 mm^{-1}.

Table 8B shows numeric values of the conic constant K and aspheric surface coefficients for each of the aspheric lens surfaces of the four lens elements.

TABLE 8B

Surface #	Semi-diameter	K	2nd order term	4th order term	6th order term	8th order term
R1	8.33E−01	0.00E+00		−3.89E−03	−3.24E−01	1.65E−01
R2	7.79E−01	0.00E+00		−1.82E−01	3.05E−01	
R3	7.03E−01	0.00E+00		−4.29E−01	1.03E+00	
R4	5.79E−01	0.00E+00		−6.64E−01	4.64E−01	
R5	4.04E−01	0.00E+00		−2.18E+00	5.19E+00	
R6	3.22E−01	0.00E+00		−3.57E+00	8.84E+00	
R7	2.76E−01	0.00E+00		−6.90E+00	−8.21E+00	
R8	3.23E−01	0.00E+00		−4.59E+00	1.53E+01	−2.65E+01

All order terms higher than the 8th order term are zeros.

FIGS. 8B-8O are a set of graphs illustrating the transverse ray fan plot of the optical imaging system 700 shown in FIG. 8A. FIGS. 8B and 8C illustrate transverse ray fan plots for an object zero degrees off axis in the y-plane and the x-plane, respectively. FIGS. 8D and 8E illustrate transverse ray fan plots for an object one degree off axis in the y-plane and the x-plane, respectively. FIGS. 8F and 8G illustrate transverse ray fan plots for an object two degrees off axis in the y-plane and the x-plane, respectively. FIGS. 8H and 8I illustrate transverse ray fan plots for an object three degrees off axis in the y-plane and the x-plane, respectively. FIGS. 8J and 8K illustrate transverse ray fan plots for an object four degrees off axis in the y-plane and the x-plane, respectively. FIGS. 8L and 8M illustrate transverse ray fan plots for an object five degrees off axis in the y-plane and the x-plane, respectively. FIGS. 8N and 8O illustrate transverse ray fan plots for an object 5.300 degrees off axis in the y-plane and the x-plane, respectively. FIG. 8P is graph illustrating the modulus of the optical transfer function (OTF) as a function of the spatial frequency (cycles/mm) in the embodiment of FIG. 8A. FIG. 8Q is graph illustrating the modulus of the optical transfer function (OTF) as a function of the field in the embodiment of FIG. 8A.

Various materials having an absorption spectrum of visible light and high transmission for near infrared wavelengths are known. For example, Ultem XH6050, Extem XH1005, Extem UH1006 are suitable materials for making lens elements of the first, second, and third embodiments described above.

The following embodiments differ from the first, second, and third embodiments described above in that they are designed for visible light having wavelengths in the range between 400 nm and 700 nm whereas the first, second, and third embodiments are designed for wavelengths of about 700 nm or longer.

Ninth Embodiment

FIG. 9A is a simplified cross sectional view of a four-element optical lens system 800 according to an embodiment of the present invention. Optical lens system 800 includes, an aperture stop AS, a first lens element L41, a second lens element L42, a third lens element L43, and a fourth lens element L44, arranged in order from the object side to the image side along the optical axis. Each lens element L41-L44 can be rotationally symmetric above the optical axis.

First lens element L41 has a positive refractive power. The object side surface of first lens element L41 has a convex portion in the vicinity of the optical axis and a convex portion in the outer circumferential region. The image-side surface of first lens element L41 has a convex portion in in the vicinity of the optical axis. Second lens element L42 has a negative refractive power and a concave image side surface in the vicinity of the optical axis. Third lens element L43 has a negative refractive power, a convex object-side along the optical axis, and a concave surface on the image side along the optical axis. Fourth lens element L44 has a negative refractive power, a concave object-side surface in the vicinity of the optical axis, and a convex image-side surface in the vicinity of the optical axis.

Optical lens system 800 also includes a filter F41 configured to pass light at visible wavelengths. Although filter F41 is shown as a single filter disposed between the fourth lens element and the image plane, filter F41 can be disposed in any other locations and can have one or more filter elements.

Referring to FIG. 9A, R1 and R2 are the respective object side and image side surface of first lens element L41. R3 and R4 are the respective object side and image side surface of second lens element L42. Similarly, R5 and R6 are the respective object-side and image-side surface of third lens element L43. Likewise, R7 and R8 are the respective object-side and image-side surface of fourth lens element L44.

In one embodiment, lens elements L41, L42, L43, and L44 each are made of a material, which passes visible light having wavelengths in the range from about 400 nm to about 700 nm.

Referring to FIG. 9A, T1 is the thickness of first lens element L41, T2 is the thickness of the second lens element L42, T3 is the thickness of the third lens element L43, and T4 is the thickness of the fourth lens element L44. Thicknesses T1-T4 are each measured along the optical axis. AC12 is the air gap between the first and second lens elements, AC23 is the air gap between the second and third

lens elements, and AC34 is the air gap between the third and fourth lens elements. Air gaps AC12, AC23, and AC34 are each measured along the optical axis. BFL denotes the back focal length, which is the distance between the image side of the fourth lens element and the image plane along the optical axis. BFL includes the thickness of the optical filter if the filter is disposed between the fourth lens element and the image plane. EFL denotes the effective focal length, which is also known as focal length.

In the following sections, ALT denotes the total thickness of the first to fourth lens elements, i.e., ALT=T1+T2+T3+T4. AAG denotes the total width of the air gaps of the first to fourth lens elements along the optical axis, i.e., AAG=AC12+AC23+AC34.

According to certain embodiments of the present invention, in order to reduce the total length of the optical lens system, the following measures can be taken: reducing the thickness of the lens elements and the air gaps between them. However, it is difficult to reduce the total thickness of the lens elements while maintaining adequate optical performance. Accordingly, the first lens element is designed to have a positive refractive power, the second lens element is designed to have a negative refractive power, the third lens element is designed to have a negative refractive power, and the fourth lens element is designed to have a negative refractive power. In order to increase the production yield and reduce manufacturing costs all fourth lens elements can be made of the same material. In one embodiment, the optical lens material has high transmission of visible light having for wavelengths in the range from 400 nm to 700 nm.

In one embodiment, all fourth lens elements L41, L42, L43, and L44 can be made of the same material and coated with an antireflective material. In certain embodiments, lens elements L41, L42, L43, and L44 may be made with different materials. In some specific embodiments, first and third lens elements L41, L43 may be made of the same first material, and second and fourth lens elements L42, L44 may be made of the same second material.

Table 9A shows numeric lens data of the lens elements of optical lens system 800 according to an embodiment of the present invention.

TABLE 9A

	Curvature Radius (1/mm)	Radius (mm)	Thickness/air gap (mm)	Refractive index	Abbe #
Object		Infinity	10000		
Aperture stop	0.00E+00		−2.79E−01		
Lens 1	1.05E+00	9.53E−01	T1 = 6.10E−01	1.544102	5.61E+01
	−3.54E−01	−2.83E+00	AC12 = 5.00E−02		
Lens 2	5.23E−02	1.91E+01	T2 = 2.40E−01	1.639753	23.35202
	8.11E−01	1.23E+00	AC23 = 6.48E−01		
Lens 3	2.83E−01	3.54E+00	T3 = 2.40E−01	1.544102	5.61E+01
	1.20E+00	8.32E−01	AC34 = 3.63E−01		
Lens 4	−4.53E−01	−2.21E+00	T4 = 2.40E−01	1.544102	5.61E+01
	−8.91E−02	−1.12E+01	AC4F = 1.00E−01		
filter	0.00E+00		TF = 2.10E−01	1.5168	64.16
	0.00E+00		ACFP = 3.00E−01		
Image plane	0.00E+00		0.00E+00		

In this embodiment, the effective focal length (EFL) is 3.9999 mm, the half field of view (HFOV) is 7 degrees. The F number is 2.80. The image height is 0.4916 mm. The total length TTL from the object-side surface of the first lens element to the image plane is 3.0414 mm. The telephoto ratio is 0.75. The angular magnification is 2.4854. The diameter of the aperture stop is 1.666 mm. The diameter of the filter is 0.892 mm. AAG is 1.061 mm. The ratio of AAG/T3 is greater than 4. The ratio of AC23/T3 is greater than 2.

In this embodiment, the first lens element has a curvature radius R1 of 1.05 mm^{-1} and a curvature radius R2 of −0.364 mm^{-1}. The second lens element has a curvature radius R3 of 0.0523 mm^{-1} and a curvature radius R4 of 0.811 mm^{-1}. The third lens element has a curvature radius R5 of 0.283 mm^{-1} and a curvature radius R6 of 1.20 mm^{-1}. The fourth lens element has a curvature radius R7 of −0.453 mm^{-1} and a curvature radius R8 of −0.0891 mm^{-1}.

Table 9B shows numeric values of the conic constant K and aspheric surface coefficients for each of the aspheric lens surfaces of the four lens elements.

TABLE 9B

Surface #	Semi-diameter (mm)	K	2nd order term	4th order term	6th order term	8th order term
R1	7.14E−01	0.00E+00		−3.16E−02	−5.23E−02	−4.19E−01
R2	6.74E−01	0.00E+00		−1.14E−01	1.49E−01	
R3	6.11E−01	0.00E+00		−4.18E−01	9.29E−01	
R4	5.01E−01	0.00E+00		−1.80E−01	7.58E−01	
R5	3.87E−01	0.00E+00		−4.42E−01	−2.45E+00	
R6	3.60E−01	0.00E+00		−8.90E−01	−4.12E−01	
R7	3.64E−01	0.00E+00		−3.81E+00	2.65E+00	
R8	4.31E−01	0.00E+00		−3.48E+00	7.53E+00	−9.47E+00

All order terms higher than the 8th order term are zeros.

FIGS. 9B-9Q are a set of graphs illustrating the transverse ray fan plot of the optical imaging system 800 shown in FIG. 9A. FIGS. 9B and 9C illustrate transverse ray fan plots for an object zero degrees off axis in the y-plane and the x-plane, respectively. FIGS. 9D and 9E illustrate transverse ray fan plots for an object one degree off axis in the y-plane and the x-plane, respectively. FIGS. 9F and 9G illustrate transverse ray fan plots for an object two degrees off axis in the y-plane

and the x-plane, respectively. FIGS. **9**H and **9**I illustrate transverse ray fan plots for an object three degrees off axis in the y-plane and the x-plane, respectively. FIGS. **9**J and **9**K illustrate transverse ray fan plots for an object four degrees off axis in the y-plane and the x-plane, respectively. FIGS. **9**L and **9**M illustrate transverse ray fan plots for an object five degrees off axis in the y-plane and the x-plane, respectively. FIGS. **9**N and **9**O illustrate transverse ray fan plots for an object six degrees off axis in the y-plane and the x-plane, respectively. FIGS. **9**P and **9**Q illustrate transverse ray fan plots for an object seven degrees off axis in the y-plane and the x-plane, respectively.

FIG. **9**R is graph illustrating the modulus of the optical transfer function (OTF) as a function of the spatial frequency (cycles/mm) in the embodiment of FIG. **9**A. FIG. **9**S is graph illustrating the modulus of the optical transfer function (OTF) as a function of the field in the embodiment of FIG. **9**A.

Tenth Embodiment

FIG. **10**A is a simplified cross sectional view of a four-element optical lens system **900** according to an embodiment of the present invention. Optical lens system **900** includes, an aperture stop AS, a first lens element L**51**, a second lens element L**52**, a third lens element L**53**, and a fourth lens element L**54**, arranged in order from the object side to the image side along the optical axis. Each lens element L**51**-L**54** can be rotationally symmetric above the optical axis.

First lens element L**51** has a positive refractive power. The object side surface of first lens element L**51** has a convex portion in the vicinity of the optical axis and a convex portion in the outer circumferential region. The image-side surface of first lens element L**51** has a convex port in in the vicinity of the optical axis. Second lens element L**52** has a negative refractive power and a concave image side surface in the vicinity of the optical axis. Third lens element L**53** has a negative refractive power, a convex object-side along the optical axis, and a concave surface on the image side along the optical axis. Fourth lens element L**54** has a negative refractive power, a concave object-side surface in the vicinity of the optical axis, and a convex image-side surface in the vicinity of the optical axis.

Optical lens system **900** also includes a filter F**51** configured to pass light at visible wavelengths. Although filter F**51** is shown as a single filter disposed between the fourth lens element and the image plane, filter F**51** can be disposed in any other locations and can have one or more filter elements.

Referring to FIG. **10**A, R**1** and R**2** are the respective object side and image side surface of first lens element L**51**. R**3** and R**4** are the respective object side and image side surface of second lens element L**52**. Similarly, R**5** and R**6** are the respective object-side and image-side surface of third lens element L**53**. Likewise, R**7** and R**8** are the respective object-side and image-side surface of fourth lens element L**54**.

In one embodiment, lens elements L**51**, L**52**, L**53**, and L**54** each are made of a material, which passes visible light having wavelengths in the range from about 400 nm to about 700 nm.

Referring to FIG. **10**A, T**1** is the thickness of first lens element L**51**, T**2** is the thickness of the second lens element L**52**, T**3** is the thickness of the third lens element L**53**, and T**4** is the thickness of the fourth lens element L**54**. Thicknesses T**1**-T**4** are each measured along the optical axis. AC**12** is the air gap between the first and second lens elements, AC**23** is the air gap between the second and third lens elements, and AC**34** is the air gap between the third and fourth lens elements. Air gaps AC**12**, AC**23**, and AC**34** are each measured along the optical axis. BFL denotes the back focal length, which is the distance between the image side of the fourth lens element and the image plane along the optical axis. BFL includes the thickness of the optical filter if the filter is disposed between the fourth lens element and the image plane. EFL denotes the effective focal length, which is also known as focal length.

In the following sections, ALT denotes the total thickness of the first to fourth lens elements, i.e., ALT=T**1**+T**2**+T**3**+T**4**. AAG denotes the total width of the air gaps of the first to fourth lens elements along the optical axis, i.e., AAG=AC**12**+AC**23**+AC**34**.

According to certain embodiments of the present invention, in order to reduce the total length of the optical lens system, the following measures can be taken: reducing the thickness of the lens elements and the air gaps between them. However, it is difficult to reduce the total thickness of the lens elements while maintaining adequate optical performance. Accordingly, the first lens element is designed to have a positive refractive power, the second lens element is designed to have a negative refractive power, the third lens element is designed to have a negative refractive power, and the fourth lens element is designed to have a negative refractive power. In order to increase the production yield and reduce manufacturing costs all fourth lens elements can be made of the same material. In one embodiment, the optical lens material has high transmission of visible light having for wavelengths in the range from 400 nm to 700 nm.

In one embodiment, all fourth lens elements L**51**, L**52**, L**53**, and L**54** can be made of the same material and coated with an antireflective material. In certain embodiments, lens elements L**51**, L**52**, L**53**, and L**54** may be made with different materials. In some specific embodiments, first and third lens elements L**51**, L**53** may be made of a same first material, and second and fourth lens elements L**52**, L**54** may be made of a same second material.

Table 10A shows numeric lens data of the lens elements of optical lens system **900** according to an embodiment of the present invention.

TABLE 10A

	Curvature Radius (1/mm)	Radius (mm)	Thickness/air gap (mm)	Refractive index	Abbe #
Object		Infinity	10000		
Aperture stop	0.00E+00		−2.79E−01		
Lens 1	1.06E+00	9.47E−01	T1 = 6.06E−01	1.544102	5.61E+01
	−3.48E−01	−2.87E+00	AC12 = 5.00E−02		
Lens 2	7.69E−02	1.30E+01	T2 = 2.40E−01	1.639753	23.35202
	8.18E−01	1.22E+00	AC23 = 6.30E−01		
Lens 3	1.87E−01	5.35E+00	T3 = 2.40E−01	1.639753	23.35202
	1.03E+00	9.73E−01	AC34 = 3.84E−01		

TABLE 10A-continued

	Curvature Radius (1/mm)	Radius (mm)	Thickness/air gap (mm)	Refractive index	Abbe #
Lens 4	−4.09E−01	−2.45E+00	T4 =	1.544102	5.61E+01
	−9.64E−02	−1.04E+01	AC4F = 1.00E−01		
filter	0.00E+00		TF = 2.10E−01	1.5168	64.16
	0.00E+00		ACFP = 3.00E−01		
Image plane	0.00E+00		0.00E+00		

In this embodiment, the effective focal length (EFL) is 3.9999 mm, the half field of view (HFOV) is 7 degrees. The F number is 2.802. The image height is 0.4916 mm. The total length TTL from the object-side surface of the first lens element to the image plane is 3.0414 mm. The telephoto ratio is 0.75. The angular magnification is 2.4597. The diameter of the aperture stop is 1.428 mm. The diameter of the filter is 0.916 mm. AAG is 1.064 mm. The ratio of AAG/T3 is greater than 4. The ratio of AC23/T3 is greater than 2.

In this embodiment, the first lens element has a curvature radius R1 of 1.06 mm^{-1} and a curvature radius R2 of −0.348 mm^{-1}. The second lens element has a curvature radius R3 of 0.0769 mm^{-1} and a curvature radius R4 of 0.818 mm^{-1}. The third lens element has a curvature radius R5 of 0.187 mm^{-1} and a curvature radius R6 of 1.03 mm^{-1}. The fourth lens element has a curvature radius R7 of −0.409 mm^{-1} and a curvature radius R8 of −0.0964 mm^{-1}.

Table 10B shows numeric values of the conic constant K and aspheric surface coefficients for each of the aspheric lens surfaces of the four lens elements.

TABLE 10B

Surface #	Semi-diameter (mm)	K	2nd order term	4th order term	6th order term	8th order term
R1	7.14E−01	0.00E+00		−4.00E−02	−6.83E−02	−4.03E−01
R2	6.74E−01	0.00E+00		−1.01E−01	1.49E−01	
R3	6.11E−01	0.00E+00		−3.94E−01	9.39E−01	
R4	5.02E−01	0.00E+00		−2.19E−01	7.31E−01	
R5	3.82E−01	0.00E+00		−7.77E−01	−2.24E+00	
R6	3.65E−01	0.00E+00		−1.16E+00	−6.59E−01	
R7	3.67E−01	0.00E+00		−3.44E+00	1.73E−01	
R8	4.33E−01	0.00E+00		−3.14E+00	5.57E+00	−5.71E+00

All order terms higher than the 8th order term are zeros.

FIGS. 10B-10Q are a set of graphs illustrating the transverse ray fan plot of the optical imaging system 900 shown in FIG. 10A. FIGS. 10B and 10C illustrate transverse ray fan plots for an object zero degrees off axis in the y-plane and the x-plane, respectively. FIGS. 10D and 10E illustrate transverse ray fan plots for an object one degree off axis in the y-plane and the x-plane, respectively. FIGS. 10F and 10G illustrate transverse ray fan plots for an object two degrees off axis in the y-plane and the x-plane, respectively. FIGS. 10H and 10I illustrate transverse ray fan plots for an object three degrees off axis in the y-plane and the x-plane, respectively. FIGS. 10J and 10K illustrate transverse ray fan plots for an object four degrees off axis in the y-plane and the x-plane, respectively. FIGS. 10L and 10M illustrate transverse ray fan plots for an object five degrees off axis in the y-plane and the x-plane, respectively. FIGS. 10N and 10O illustrate transverse ray fan plots for an object six degrees off axis in the y-plane and the x-plane, respectively. FIGS. 10P and 10Q illustrate transverse ray fan plots for an object seven degrees off axis in the y-plane and the x-plane, respectively.

FIG. 10R is graph illustrating the modulus of the optical transfer function (OTF) as a function of the spatial frequency (cycles/mm) in the embodiment of FIG. 10A. FIG. 10S is graph illustrating the modulus of the optical transfer function (OTF) as a function of the field in the embodiment of FIG. 10A.

Eleventh Embodiment

FIG. 11A is a simplified cross sectional view of a four-element optical lens system 1000 according to an embodiment of the present invention. Optical lens system 1000 includes, an aperture stop AS, a first lens element L61, a second lens element L62, a third lens element L63, and a fourth lens element L64, arranged in order from the object side to the image side along the optical axis. Each lens element L61-L64 can be rotationally symmetric above the optical axis.

First lens element L61 has a positive refractive power. The object side surface of first lens element L61 has a convex portion in the vicinity of the optical axis and a convex portion in the outer circumferential region. The image-side surface of first lens element L61 has a convex portion in the vicinity of the optical axis. Second lens element L62 has a negative refractive power; the image-side surface of second lens element L62 has a concave portion in the vicinity of the optical axis. Third lens element L63 has a negative refractive power, the object-side surface of third lens element L63 has a convex portion in the proximity of the optical axis, and the image-side surface of third lens element L63 has a concave portion in the proximity of the optical axis. Fourth lens element L64 has a negative refractive power, a concave object-side surface in the vicinity of the optical axis, and a convex image-side surface in the vicinity of the optical axis.

Optical lens system 1000 also includes a filter F61 configured to pass light at visible wavelengths. Although filter F61 is shown as a single filter disposed between the fourth lens element and the image plane, filter F61 can be disposed in any other locations and can have one or more filter elements.

Referring to FIG. 11A, R1 and R2 are the respective object side and image side surface of first lens element L61. R3 and R4 are the respective object side and image side surface of second lens element L62. Similarly, R5 and R6 are the respective object-side and image-side surface of third

lens element L63. Likewise, R7 and R8 are the respective object-side and image-side surface of fourth lens element L64.

In one embodiment, lens elements L61, L62, L63, and L64 each are made of a material, which passes visible light having wavelengths in the range from about 400 nm to about 700 nm.

Referring to FIG. 11A, T1 is the thickness of first lens element L61, T2 is the thickness of the second lens element L62, T3 is the thickness of the third lens element L63, and T4 is the thickness of the fourth lens element L64. Thicknesses T1-T4 are each measured along the optical axis. AC12 is the air gap between the first and second lens elements, AC23 is the air gap between the second and third lens elements, and AC34 is the air gap between the third and fourth lens elements. Air gaps AC12, AC23, and AC34 are each measured along the optical axis. BFL denotes the back focal length, which is the distance between the image side of the fourth lens element and the image plane along the optical axis. BFL includes the thickness of the optical filter if the filter is disposed between the fourth lens element and the image plane. EFL denotes the effective focal length, which is also known as focal length.

In the following sections, ALT denotes the total thickness of the first to fourth lens elements, i.e., ALT=T1+T2+T3+T4. AAG denotes the total width of the air gaps of the first to fourth lens elements along the optical axis, i.e., AAG=AC12+AC23+AC34.

According to certain embodiments of the present invention, in order to reduce the total length of the optical lens system, the following measures can be taken: reducing the thickness of the lens elements and the air gaps between them. However, it is difficult to reduce the total thickness of the lens elements while maintaining adequate optical performance. Accordingly, the first lens element is designed to have a positive refractive power, the second lens element is designed to have a negative refractive power, the third lens element is designed to have a negative refractive power, and the fourth lens element is designed to have a negative refractive power. In order to increase the production yield and reduce manufacturing costs all fourth lens elements can be made of the same material. In one embodiment, the optical lens material has high transmission of visible light having for wavelengths in the range from 400 nm to 700 nm.

In one embodiment, all fourth lens elements L61, L62, L63, and L64 can be made of the same material and coated with an antireflective material. In certain embodiments, lens elements L61, L62, L63, and L64 may be made with different materials. In some specific embodiments, first and third lens elements L61, L43 may be made of a first material and second and fourth lens elements L62, L64 may be made of a second material.

Table 11A shows numeric lens data of the lens elements of optical lens system 1000 according to an embodiment of the present invention.

TABLE 11A

	Curvature Radius (1/mm)	Radius (mm)	Thickness/air gap (mm)	Refractive index	Abbe #
Object		Infinity	10,000		
Aperture stop			−2.79E−01		
Lens 1	1.05E+00	9.51E−01	T1 = 6.08E−01	1.544102	56.1
	−3.52E−01	−2.84E+00	AC12 = 5.00E−02		
Lens 2	6.34E−02	1.58E+01	T2 = 2.40E−01	1.639753	23.35202
	8.13E−01	1.23E+00	AC23 = 6.38E−01		
Lens 3	1.97E−01	5.08E+00	T3 = 2.40E−01	1.544102	56.1
	1.07E+00	9.38E−01	AC34 = 3.74E−01		
Lens 4	−5.61E−01	−1.78E+00	T4 = 2.40E−01	1.639753	23.35202
	−1.93E−01	−5.18E+00	AC4F = 1.00E−01		
filter			TF = 2.10E−01	1.5168	64.16
			ACFP = 3.00E−01		
Image plane			0.00E+00		

In this embodiment, the effective focal length (EFL) is 3.9999 mm, the half field of view (HFOV) is 7 degrees. The F number is 2.802. The image height is 0.4916 mm. The total length TTL from the object-side surface of the first lens element to the image plane is 3.00 mm. The telephoto ratio (TTL/EFL) is 0.75. The angular magnification is 2.4877. The diameter of the aperture stop is 1.428 mm. The diameter of the filter is 0.894 mm. AAG is 1.062 mm. The ratio of AAG/T3 is greater than 4. The ratio of AC23/T3 is greater than 2.

Table 11B shows numeric values of the conic constant K and aspheric surface coefficients for each of the aspheric lens surfaces of the four lens elements.

TABLE 11B

Surface #	Semi-diameter (mm)	K	2nd order term	4th order term	6th order term	8th order term
R1	7.14E−01	0.00E+00		−3.44E−02	−5.86E−02	−4.09E−01
R2	6.74E−01	0.00E+00		−1.06E−01	1.45E−01	
R3	6.10E−01	0.00E+00		−4.01E−01	9.20E−01	
R4	5.00E−01	0.00E+00		−1.77E−01	7.64E−01	
R5	3.87E−01	0.00E+00		−3.88E−01	−2.40E+00	
R6	3.61E−01	0.00E+00		−7.36E−01	−6.49E−01	
R7	3.62E−01	0.00E+00		−3.43E+00	1.47E+00	
R8	4.32E−01	0.00E+00		−3.02E+00	6.15E+00	−7.76E+00

All order terms higher than the 8th order term are zeros.

FIGS. 11B-11Q are a set of graphs illustrating the transverse ray fan plot of the optical imaging system 1000 shown

in FIG. **11**A. FIGS. **11**B and **11**C illustrate transverse ray fan plots for an object zero degrees off axis in the y-plane and the x-plane, respectively. FIGS. **11**D and **11**E illustrate transverse ray fan plots for an object one degree off axis in the y-plane and the x-plane, respectively. FIGS. **11**F and **11**G illustrate transverse ray fan plots for an object two degrees off axis in the y-plane and the x-plane, respectively. FIGS. **11**H and **11**I illustrate transverse ray fan plots for an object three degrees off axis in the y-plane and the x-plane, respectively. FIGS. **11**J and **11**K illustrate transverse ray fan plots for an object four degrees off axis in the y-plane and the x-plane, respectively. FIGS. **11**L and **11**M illustrate transverse ray fan plots for an object five degrees off axis in the y-plane and the x-plane, respectively. FIGS. **11**N and **11**O illustrate transverse ray fan plots for an object six degrees off axis in the y-plane and the x-plane, respectively. FIGS. **11**P and **11**Q illustrate transverse ray fan plots for an object seven degrees off axis in the y-plane and the x-plane, respectively.

FIG. **11**R is graph illustrating the modulus of the optical transfer function (OTF) as a function of the spatial frequency (cycles/mm) in the embodiment of FIG. **11**A. FIG. **11**S is graph illustrating the modulus of the optical transfer function (OTF) as a function of the field in the embodiment of FIG. **11**A.

Twelfth Embodiment

FIG. **12**A is a simplified cross-section view of a four-element optical lens system **1100** according to a first embodiment of the present invention. Optical lens system **1100** comprises an aperture stop AS, a first lens element L**11**, a second lens element L**12**, a third lens element L**13**, and a fourth lens element L**14**, arranged in order from the object side to the image side along the optical axis. Each lens element L**11**-L**14** can be rotationally symmetric above the optical axis.

First lens element L**11** has a positive refractive power, a convex object-side portion in the vicinity of the optical axis, a convex object-side portion in the outer circumferential region, a concave image-side portion in the vicinity of the optical axis, and a convex image-side portion in the outer circumferential region. Second lens element L**12** has a negative refractive power, a concave object-side portion in the vicinity of the optical axis, a concave object-side portion in the outer circumferential region, a convex image-side portion in the vicinity of the optical axis, and a convex image side portion in the outer circumferential region. Third lens element L**13** has a positive refractive power, a concave object-side portion in the vicinity of the optical axis, a concave object-side portion in the outer circumferential region, a convex image-side portion in the vicinity of the optical axis, and a convex image side portion in the outer circumferential region. Fourth lens element L**14** has a negative refractive power, a convex object-side portion in the vicinity of the optical axis, a concave object-side portion in the outer circumferential region, a concave image-side portion in the vicinity of the optical axis, and a convex image-side portion in the outer circumferential region.

Optical lens system **1100** further includes a filter F**11** disposed between fourth lens element L**14** and an imaging sensor. In an embodiment, filter F**11** may be made of glass that is opaque to visible light and transparent to infrared radiation.

Optical lens system **1100** further includes an aperture stop AS disposed in front of first lens element L**11**.

Referring to FIG. **12**A, R**1** and R**2** are the respective object side and image side surface of first lens element L**11**. R**3** and R**4** are the respective object side and image side surface of second lens element L**12**. Similarly, R**5** and R**6** are the respective object-side and image-side surface of third lens element L**13**. Likewise, R**7** and R**8** are the respective object-side and image-side surface of fourth lens element L**14**.

In one embodiment, lens elements L**11**, L**12**, L**13**, and L**14** each are made of the same material, which passes near infrared light having a wavelength in a range about 900 nm to about 980 nm and have a high absorption for visible light. In a specific embodiment, the material of lens elements L**11**, L**12**, L**13**, and L**14** has a transmission peak at 940 nm. In some embodiments, lens elements may be made of plastic.

Still referring to FIG. **12**A, T**1** is the thickness of first lens element L**11**, T**2** is the thickness of the second lens element L**12**, T**3** is the thickness of the third lens element L**13**, and T**4** is the thickness of the fourth lens element L**14**. Thicknesses T**1**-T**4** are each measured along the optical axis. G**12** is the air gap between the first and second lens elements. G**23** is the air gap between the second and third lens elements, and G**34** is the air gap between the third and fourth lens elements. Air gaps G**12**, G**23**, and G**34** are each measured along the optical axis. BFL denotes the back focal length, which is the distance between the image side of the fourth lens element and the image plane along the optical axis. BFL includes the thickness of the optical filter if the filter is disposed between the fourth lens element and the image plane. EFL denotes the effective focal length, which is also known as focal length. MBFL denotes the distance between the highest protruding point M of the image side of the fourth lens element and the image plane along the optical axis.

In the following sections, ALT denotes the total thickness of the first to fourth lens elements, i.e., ALT=T**1**+T**2**+T**3**+T**4**. AAG denotes the total width of the air gaps of the first to fourth lens elements along the optical axis, i.e., AAG=G**12**+G**23**+G**34**.

Table 12A shows numeric lens data of the lens elements of optical lens system **1100** according to an embodiment of the present invention. All four lens elements are made of the same plastic material to simplify the manufacturing process and reduce the manufacturing costs.

TABLE 12A

	Radius (mm)	Thickness/air gap (mm)	Refractive index	Abbe #	Focal length
Aper. Stop	infinity	−0.091			
Lens 11	1.607	T1 = 0.550	1.54	49.9	3.144
R1					
R2	30.068	G12 = 0.186			
Lens 12	−12.787	T2 = 0.300	1.63	23.3	−34.242
R3					
R4	−33.168	G23 = 0.345			
Lens 13	−1.002	T3 = 0.453	1.63	23.3	2.093
R5					
R6	−0.658	G34 = 0.080			
Lens 14	1.844	T4 = 0.462	1.54	49.9	−2.572
R7					
R8	0.720	G4F = 0.501			
filter	infinity	TF = 0.500			
Filter to image plane	infinity	GFP = 0.298			
Image plane	infinity				

In this embodiment, the effective focal length (EFL) is 2.5 mm, the half field of view (HFOV) is 39.5 degrees. The F

number is 2.0. The MBFL is 0.973 mm. The total length from the object-side surface of the first lens element to the image plane is about 3.675 mm. The object-side and image-side surfaces of the four lens elements are even aspheric.

According to this embodiment, the air gap G**12** between the first and second lens elements is about 0.186 mm along the optic axis. The air gap G**23** between the second and third lens elements is about 0.345 mm, and the air gap G**34** between the third and fourth lens elements is about 0.08 mm along the optical axis. The filter may be made of glass and has a thickness of about 0.5 mm. The filter is disposed at about 0.501 mm from the image-side of fourth lens element L**14** and 0.298 mm from the image plane along the optical axis. In the embodiment, the sum of all air gaps AAG between the first through the fourth lens elements is 0.611 mm. The total thickness ALT of the first to fourth lens elements is 1.765 mm.

According to certain embodiments of the present invention, in order to reduce the total length of the optical lens system, the following measures can be taken: reducing the thickness of the lens elements and the air gaps between them. However, it is difficult to reduce the total thickness of the lens elements while maintaining adequate optical performance. Accordingly, the first lens element is designed to have a positive refractive power, the second lens element is designed to have a negative refractive power, and the third lens element is designed to have a positive refractive power. In order to increase the production yield and reduce manufacturing costs all three lens elements can be made of the same material. In one embodiment, the optical lens material has an absorption spectrum of visible light with a wavelength in the range between 400 nm and 700 nm, while having high transmission for wavelengths above 850 nm, preferably between 900 nm and 980 nm, and more preferably between 930 nm and 950 nm.

According to the twelfth embodiment, the first lens element has a positive refractive power, a convex portion on the object-side in the vicinity of the optical axis, and a concave portion on the image-side in the vicinity of the optical axis. The second lens element has a negative refractive power, a concave portion on the object-side in the vicinity of the optical axis, and a convex surface on the image-side in the vicinity of the optical axis. The third lens element has a positive refractive power, a concave portion on the object-side in the vicinity of the optical axis, and a convex portion in the vicinity of the optical axis. The fourth lens element has a negative a refractive power, a convex image-side portion in the vicinity of the optical axis, and a convex image-side portion in the vicinity of the optical axis. The object-side and image-side surfaces of the four lens elements are even aspheric. The combination of these four lens elements provides the desired lens system quality.

Table 12B shows numeric lens data of the conic constant K and aspheric surface coefficients as for each of the lens surfaces of optical lens system **1100** according to the twelfth embodiment of the present invention.

TABLE 12B

Surface #	K	a4	a6	a8	a10	a12	a14	a16
R1	0.00E+00	−7.16E−02	2.19E−01	−1.50E+00	3.83E+00	−5.47E+00	2.28E+00	0.00E+00
R2	0.00E+00	−1.90E−01	−4.84E−01	3.70E−01	−2.33E−01	0.00E+00	0.00E+00	0.00E+00
R3	0.00E+00	−3.15E−01	−1.14E−01	−1.78E+00	4.07E+00	−1.95E+00	0.00E+00	0.00E+00
R4	0.00E+00	−6.93E−02	7.66E−02	−1.05E+00	2.20E+00	−2.10E+00	8.74E−01	0.00E+00
R5	0.00E+00	2.70E−01	−7.99E−02	4.74E−01	−1.33E+00	1.86E+00	−7.59E−01	0.00E+00
R6	−8.98E−01	5.34E−01	−1.27E+00	2.83E+00	−4.12E+00	3.55E+00	−1.20E+00	0.00E+00
R7	0.00E+00	−2.44E−01	9.75E−02	−2.58E−02	−3.57E−03	4.44E−03	−8.67E−04	0.00E+00
R8	−5.22E+00	−1.09E−01	7.43E−02	−5.12E−02	2.54E−02	−8.35E−03	1.56E−03	−1.24E−04

All order terms higher than the 16th order term are zeros.

FIG. **12**B is a set of graphs illustrating the astigmatism for the sagittal and tangential image surface in the embodiment of FIG. **12**A.

FIG. **12**C is the optical distortion of the embodiment of FIG. **12**A.

Thirteenth Embodiment

FIG. **13**A is a simplified cross sectional view of a four-element optical lens system **1200** according to an embodiment of the present invention. Optical lens system **1200** includes an aperture stop AS, a first lens element L**21**, a second lens element L**22**, a third lens element L**23**, and a fourth lens element L**24**, arranged in order from the object side to the image side along the optical axis. Each lens element L**21**-L**24** can be rotationally symmetric above the optical axis.

First lens element L**21** has a positive refractive power, a convex object-side portion in the vicinity of the optical axis, a convex object-side portion in the outer circumferential region, a concave image-side portion in the vicinity of the optical axis, and a convex image-side portion in the outer circumferential region. Second lens element L**22** has a positive refractive power, a convex object-side portion in the vicinity of the optical axis, a concave object-side portion in the outer circumferential region, a concave image-side portion in the vicinity of the optical axis and a convex image side portion in the outer circumferential region. Third lens element L**23** has a positive refractive power, a concave object-side portion along the optical axis, a concave object-side portion in the outer circumferential region, a convex image-side portion in the vicinity of the optical axis, and a concave image side portion on the image side in the outer circumferential region. Fourth lens element L**24** has a negative refractive power, a convex object-side portion in the vicinity of the optical axis, a concave object-side portion in the outer circumferential region, a concave image-side portion in the vicinity of the optical axis, and a convex image-side portion in the outer circumferential region.

Optical lens system **1200** also includes a filter F**21** configured to block the passage of light at visible wavelengths. In some embodiments, the filter filters out wavelengths below about 700 nm. The optical filter blocks shorter wavelengths of the visible spectrum and passes through wavelengths above about 700 nm, preferably wavelengths in the range between 900 nm and 980 nm. The filter improves the infrared performance of the imaging lens system **1200** by reducing interference from other light sources. Although filter F**21** is shown as a single filter disposed between the fourth lens element and the image plane, filter F**21** can be

disposed in any other locations and can have one or more filter elements. Filter F**21** can be similar to filter F**11** described above.

As shown in FIG. **13**A, R**1** and R**2** are the respective object side and image side surface of first lens element L**21**. R**3** and R**4** are the respective object side and image side surface of second lens element L**22**. Similarly, R**5** and R**6** are the respective object-side and image-side surface of third lens element L**23**. Likewise, R**7** and R**8** are the respective object-side and image-side surface of fourth lens element L**24**.

In one embodiment, lens elements L**21**, L**22**, L**23**, and L**24** each pass near infrared light having a wavelength about 900 nm. In another embodiment, the material of the lens elements L**21**, L**22**, L**23**, and L**24** has a high absorption for visible light and a high transmission for near infrared light longer than 900 nm, preferably at 940 nm.

Referring to FIG. **13**A, T**1** is the thickness of first lens element L**21**, T**2** is the thickness of the second lens element L**22**, T**3** is the thickness of the third lens element L**23**, and T**4** is the thickness of the fourth lens element L**24**. Thicknesses T**1**-T**4** are each measured along the optical axis. G**12** is the air gap between the first and second lens elements. G**23** is the air gap between the second and third lens elements, and G**34** is the air gap between the third and fourth lens elements. Air gaps G**12**, G**23**, and G**34** are each measured along the optical axis. BFL denotes the back focal length, which is the distance between the image side of the fourth lens element and the image plane along the optical axis. BFL includes the thickness of the optical filter if the filter is disposed between the fourth lens element and the image plane. MBFL denotes the distance between the highest protruding point M of the image side of the fourth lens element and the image plane along the optical axis. EFL denotes the effective focal length, which is also known as focal length.

In the following sections, ALT denotes the total thickness of the first to fourth lens elements, i.e., ALT=T**1**+T**2**+T**3**+T**4**. AAG denotes the total width of the air gaps of the first to fourth lens elements along the optical axis, i.e., AAG=G**12**+G**23**+G**34**. In an embodiment, AAG is 0.545 mm. The ratio of AAG/T**3** is 0.971. The ratio of EFL/T**4** satisfies the relation of 6.0≤EFL/T**4**. The ratio of G**34**/T**3** satisfies the relation 0.01≤AC**34**/T**3**.

According to certain embodiments of the present invention, in order to reduce the total length of the optical lens system, the following measures can be taken: reducing the thickness of the lens elements and the air gaps between them. However, it is difficult to reduce the total thickness of the lens elements while maintaining adequate optical performance. Accordingly, the first lens element is designed to have a positive refractive power, the second lens element is designed to have a positive refractive power, the third lens element is designed to have a positive refractive power, and the fourth lens element is designed to have a negative refractive power. In one embodiment, the optical lens material has an absorption spectrum of visible light in the range from 400 nm to 700 nm, while having high transmission for wavelengths above 850 nm, preferably between 900 nm and 980 nm, and more preferably between 930 nm and 950 nm.

In one embodiment, all fourth lens elements L**21**, L**22**, L**23**, and L**24** can be made of a material and coated with an antireflective material optimized for near-infrared radiation. In a preferred embodiment, the antireflective material has a transmission peak at about 940 nm.

Table 13A shows numeric lens data of the lens elements of optical lens system **1200** according to an embodiment of the present invention. All four lens elements are made of the same material to simplify the manufacturing process and reduce the manufacturing costs.

TABLE 13A

	Radius (mm)	Thickness/air gap (mm)	Refractive index	Abbe #	Focal length
Aper. stop	infinity	−0.071			
Lens 21	1.830	T1 = 0.550	1.54	49.9	3.656
R1					
R2	24.489	G12 = 0.146			
Lens 22	6.577	T2 = 0.300	1.63	23.3	25.663
R3					
R4	11.131	G23 = 0.319			
Lens 23	−1.032	T3 = 0.561	1.63	23.3	2.069
R5					
R6	−0.685	G34 = 0.080			
Lens 24	1.603	T4 = 0.407	1.54	49.9	−2.586
R7					
R8	0.678	G4F = 0.595			
filter	infinity	TF = 0.500			
Filter to image plane	infinity	GFP = 0.298			
Image plane	infinity				

In this embodiment, the effective focal length (EFL) is 2.51 mm, the half field of view (HFOV) is 39.5 degrees. The F number is 2.0. The BFL is 1.067 mm. The total length TTL from the object-side surface of the first lens element to the image plane is 3.756 mm.

Table 13B shows numeric values of the conic constant K and aspheric surface coefficients for each of the aspheric lens surfaces of the four lens elements.

TABLE 13B

Surface #	K	a4	a6	a8	a10	a12	a14	a16
R1	0.00E+00	0.00E+00	1.71E−01	−1.22E+00	−1.22E+00	−4.01E+00	1.54E+00	0.00E+00
R2	0.00E+00	0.00E+00	−4.95E−01	7.46E−01	7.46E−01	0.00E+00	0.00E+00	0.00E+00
R3	0.00E+00	0.00E+00	−7.41E−01	3.04E−01	3.04E−01	−6.52E−01	0.00E+00	0.00E+00
R4	0.00E+00	0.00E+00	−5.73E−01	7.11E−01	7.11E−01	2.20E−01	−1.13E−01	0.00E+00
R5	0.00E+00	0.00E+00	−5.59E−02	−3.58E−01	−3.58E−01	−1.57E+00	5.20E−01	0.00E+00
R6	−9.90E−01	−9.90E−01	−1.23E+00	2.18E+00	2.18E+00	1.88E+00	−6.10E−01	0.00E+00
R7	0.00E+00	0.00E+00	1.07E−02	1.21E−01	1.21E−01	4.75E−02	−7.28E−03	0.00E+00
R8	−4.82E+00	−4.82E+00	3.18E−02	3.54E−03	3.54E−03	3.97E−03	−6.74E−04	4.07E−05

All order terms higher than the 16th order term are zeros.

FIG. **13**B is a set of graphs illustrating the astigmatism for the sagittal and tangential image surface in the embodiment of FIG. **13**A.

FIG. **13**C is the optical distortion of the embodiment of FIG. **13**A.

Fourteenth Embodiment

FIG. **14** is a simplified cross-sectional view of a camera lens system **1300** according to an embodiment of the present

invention. Camera lens system **1300** is shown as including a housing unit **401**, in which a barrel **402** and a holder **404** are integrally formed (a broken line delineates barrel **402** and holder **404**). Housing unit **401** has an opening **406** to let light enter a lens group **408**. Lens group **408** is mounted within barrel **402**, which is the front portion of housing unit **401**. Lens group **408** may include four lens elements L**1** through L**4**, which may be lens elements L**11**-L**14** of FIG. **12**A or lens elements L**21**-L**24** of FIG. **13**A. Housing unit **401** may also include a filter **410** mounted between lens element L**4** and an image sensor **422** along the optical axis. Camera lens system **400** also includes a substrate **420** on which image sensor **422** mounted on substrate **420**. Housing unit **401** is attached to substrate **420** during manufacture. In an embodiment, housing unit **401** can be coupled to substrate **420** with an adhesive. Lens barrel **402** and holder **404** can be intergrally formed as housing unit **401** along the optical axis.

Fifteenth Embodiment

FIG. **15** is a simplified cross-sectional view of a camera lens system **1400** according to an embodiment of the present invention. Camera lens system **1400** is shown as including a housing unit **501**, which contains an integrally formed barrel **502** and holder **504**. Housing unit **501** may include a concave portion **505** for accommodating a light source **512**. Housing unit **501** may also include a protection cover **514** disposed in front of concave portion **505** to protect light source **512**. In an embodiment, concave portion **505** may be integrally formed with holder **504** so that barrel **502**, holder **504** and concave portion **505** are integrally formed. Although concave portion **505** is shown to be positioned above lens group **08**, it is to be understood that concave portion **505** can be positioned at any location in relation to the lens group, such as to the right, to the left, to the bottom, and any other locations. In an embodiment, light source **512** can be an infrared light or a near-infrared light to take a clear picture of an object even in the night. Protection cover may be a diffusion lens to diffuse light emitting from light source **512**. Since diffused light is near infrared (NIR) rays, it is not visible to people when an object is illuminated by light source **512**. Barrel **502**, holder **504** and concave portion **505** are formed with an opaque material to prevent illuminating light from radiating lens group **508** from the side. Housing unit **501** has an opening **506** to let light enter a lens group **508**. Lens group **508** is mounted within barrel **502**, which is the front portion of housing unit **501**. Lens group **508** may include lens elements L**11**-L**14** of FIG. **2**A or lens elements L**21**-L**24** of FIG. **3**A. Housing unit **501** may also include a filter **510** mounted along the optical axis to absorb visible light in wavelengths between 400 nm and 700 nm and pass though wavelengths in the range between 900 nm and 980 nm. Camera lens system **500** also includes a substrate **520** and an image sensor **522** mounted on substrate **520**.

In other embodiment, light source **512** may be a lens system having a light source structure of a projector or a LED structure having a predetermined light-projecting angle, that is not a part of housing unit **501**. In other words, light source **512** can be an independent illuminating structure that is separated from housing unit **501** and lens group **508**. In some specific embodiments, light source **512** can be an illuminating structure that is not even part of optical lens system **500**. In an exemplary embodiment, light source **512** can be directional infrared light or near-infrared light that illuminates an object to enhance visibility of buried structure beneath the surface of the illuminated object.

In some specific embodiments, an object whose image is to be captured is illuminated by a specific light source. The surface of the object is scanned to produce 3-dimensional (3D) image information including depth, location and other information. According to the present invention, the surface of the object can be scanned under a first scanning angle with regard to the near-infrared (NIR) rays to obtain a first 3D image information A, then the object is rotated and the surface of the object is scanned anew under a second scanning angle with regard to the NIR rays to obtain a second 3D image information B. The object can be further rotated and its surface is scanned under a third angle, a fourth angle, and so forth with regard to the NIR rays to obtain respective 3D image information C, D, and so forth. The obtained 3D image information can be used to construct a 3D image of the object to be scanned. The above NIR rays can be other light forms, such as laser, or specially processed light rays. It shall be appreciated that the use of near infrared radiations is advantageous over other light radiations because infrared radiations are invisible to human eyes. Although ultraviolet (UV) light is also invisible to human eye, UV light can cause harm and damage to human eyes and to the structure of the radiated or illuminated object. Furthermore, the wavelengths of near infrared light are longer than those of UV light and visible light, the near infrared light is less prone to scatter in and absorption by plant or animal tissue.

In an embodiment, a method of forming an image includes illuminating an object to be scanned using a light source, capturing light reflected by the object, collecting information data from the captured light, and forming an image in response to the collected information data.

In some embodiments, the first and third lens elements may be made of the same first material while the second and the fourth lens elements may be made of the same second material. The half field of view (HFOV) is between 36 degrees and 45 degrees, preferably between 39 degrees and 41 degrees. The obtained optical distortion is less than ±5%, preferably less than ±0.5%. The total length from the object-side surface of the first lens element to the image plane is less than 4.5 mm. The RI (relative illumination) is 40% or more, preferably between 40%-60%. The first and fourth lens elements have an abbe number about 49.9, and the second and the third lens elements have an abbe number of about 23.3. The combination of lens elements provides good image quality in infrared wavelengths. By having appropriate thicknesses of the lens elements, the air gaps between them, and a simple housing design, the present invention provides an easy and efficient production with good yield.

Furthermore, images obtained by the optical image system according to embodiments of the present invention not only have low optical distortion of less than ±0.5%, but also low TV distortion of less than −5%. FIG. **16**A is a graph illustrating the TV distortion and FIG. **16**B is a simplified diagram of an example raster TV distortion.

While the invention has been described with reference to illustrative embodiments, this description is not intended to be construed in a limiting sense. For example, in some embodiments, the aperture stop is disposed in front of the first lens element to improve the lens system performance. In other embodiments, the aperture strop is disposed between the first and second lens elements as in the telecentric lens, as shown in FIG. **4**. The optical lens system has only either three or four lens elements that have a refractive power. All lens elements are made of the same material having absorption in visible light, i.e., in wavelengths between 400 nm and 700 nm. All lens elements in the same

lens system are made of the same material having a high transmission for near infrared radiation. In certain embodiments, the object-side and image-side surfaces of the lens elements are coated with an antireflective coating that is optimized for near infrared light, i.e., in wavelengths above 800 nm.

It will be appreciated that, although an optical filter is shown in embodiments described above, the optical filter may be omitted if desired.

The present invention is not limited to the above-described embodiments. The invention is intended to cover all modifications and equivalents within the scope of the appended claims.

What is claimed is:

1. An optical imaging lens system comprising, in a given order from an object side to an image side, a first lens element, a second lens element, a third lens element, and a fourth lens element arranged along an optical axis, each of the first, second, third, and fourth lens elements having an object-side surface facing toward the object side and an image-side surface facing toward the image side,

the first lens element being arranged to be a lens element having positive refractive power in a first order from the object side to the image side;

the second lens element being arranged to be a lens element having refractive power in a second order from the object side to the image side, the object-side surface of the second lens element comprising a convex portion in a vicinity of the optical axis, and the image-side surface of the second lens element comprising a concave portion in a vicinity of an outer circumference of the second lens element, the object-side surface and the image-side surface of the second lens element each being an aspheric surface;

the third lens element being arranged to be a lens element having refractive power in a third order from the object side to the image side, the object-side surface and the image-side surface of the third lens element each being an aspheric surface;

the fourth lens element being arranged to be a lens element having refractive power in a fourth order from the object side to the image side, the image-side surface of the fourth lens element comprising a convex portion in a vicinity of the optical axis, the object-side surface and the image-side surface of the fourth lens element each being an aspheric surface, wherein:

a half field of view of the optical imaging lens system is defined as HFOV, an F number of the optical imaging lens system is defined as Fno, an air gap between the second and third lens elements along the optical axis is defined as G**23**, a thickness of the first lens element along the optical axis is defined as T**1**, and HFOV, Fno, G**23** and T**1** satisfy the relations:

$$2.13° \leq \mathrm{HFOV}/Fno \leq 8.75°;$$

$$0.56 \leq G23/T1 \leq 1.54.$$

2. The optical imaging lens system of claim **1** wherein a thickness of the second lens element along the optical axis is defined as T**2**, a thickness of the third lens element along the optical axis is defined as T**3**, and T**1**, T**2**, and T**3** satisfy the relation:

$$2.17 \leq (T1+T2)/T3 \leq 3.00.$$

3. The optical imaging lens system of claim **1** wherein a thickness of the second lens element along the optical axis is defined as T**2**, a thickness of the fourth lens element along the optical axis is defined as T**4**, and T**1**, T**2**, and T**4** satisfy the relation:

$$1.30 \leq (T1+T2)/T40 \leq 2.10.$$

4. The optical imaging lens system of claim **1** wherein a distance measured from the object-side surface of the first lens element to the image-side surface of the fourth lens element along the optical axis is defined as TL, and HFOV and TL satisfy the relation:

$$1.93°/\mathrm{mm} \leq \mathrm{HFOV}/TL \leq 10.55°/\mathrm{mm}.$$

5. The optical imaging lens system of claim **1** wherein a distance measured from the object-side surface of the first lens element to an image plane along the optical axis is defined as TTL, and TTL and T**1** satisfy the relation:

$$3.85 \leq TTL/T1 \leq 7.00.$$

6. The optical imaging lens system of claim **1** wherein a sum of thicknesses of the first, second, third, and fourth lens elements along the optical axis is defined as ALT, a distance between the image side of the fourth lens element and an image plane along the optical axis is defined as BFL, and ALT and BFL satisfy the relation:

$$3.63 \leq ALT/BFL \leq 15.20.$$

7. The optical imaging lens system of claim **1** wherein a thickness of the second lens element along the optical axis is defined as T**2**, a thickness of the fourth lens element along the optical axis is defined as T**4**, an air gap between the first lens element and the second lens element measured along the optical axis is defined as G**12**, and T**2**, T**4**, and G**12** satisfy the relation:

$$4.36 \leq (T2+T4)/G12 \leq 44.00.$$

8. The optical imaging lens system of claim **1** wherein a sum of thicknesses of the first, second, third, and fourth lens elements along the optical axis is defined as ALT, and ALT and G**23** satisfy the relation:

$$1.90 \leq ALT/G23 \leq 7.40.$$

9. The optical imaging lens system of claim **1** wherein an air gap between the first lens element and the second lens element measured along the optical axis is defined as G**12**, and T**1** and G**12** satisfy the relation:

$$3.39 \leq T1/G12 \leq 19.25.$$

10. The optical imaging lens system of claim **1** wherein a thickness of the second lens element along the optical axis is defined as T**2**, and T**2** and T**1** satisfy the relation:

$$0.45 \leq T2/T1 \leq 1.15.$$

11. An optical imaging lens system comprising, in a given order from an object side to an image side, a first lens element, a second lens element, a third lens element, and a fourth lens element arranged along an optical axis, each of the first, second, third, and fourth lens elements having an object-side surface facing toward the object side and an image-side surface facing toward the image side,

the first lens element being arranged to be a lens element having positive refractive power in a first order from the object side to the image side;

the second lens element being arranged to be a lens element having refractive power in a second order from the object side to the image side, the object-side surface of the second lens element comprising a convex portion in a vicinity of an outer circumference of the second lens element, and the image-side surface of the second

lens element comprising a concave portion in the vicinity of the outer circumference of the second lens element, the object-side surface and the image-side surface of the second lens element each being an aspheric surface;

the third lens element being arranged to be a lens element having refractive power in a third order from the object side to the image side, the object-side surface and the image-side surface of the third lens element each being an aspheric surface;

the fourth lens element being arranged to be a lens element having refractive power in a fourth order from the object side to the image side, the image-side surface of the fourth lens element comprising a convex portion in a vicinity of the optical axis, the object-side surface and the image-side surface of the fourth lens element each being an aspheric surface, wherein:

a half field of view of the optical imaging lens system is defined as HFOV, an F number of the optical imaging lens system is defined as Fno, an air gap between the second and third lens elements is defined as G**23**, a thickness of the first lens element along the optical axis is defined as T**1**, and HFOV, Fno, G**23** and T**1** satisfy the relations:

$$2.13° \leq HFOV/Fno \leq 8.75°;$$

$$0.56 \leq G23/T1 \leq 1.54.$$

12. The optical imaging lens system of claim **11** wherein a thickness of the second lens element along the optical axis is defined as T**2**, an air gap between the third lens element and the fourth lens element measured along the optical axis is defined as G**34**, a thickness of the third lens element along the optical axis is defined as T**3**, and T**1**, T**2**, G**34**, and T**3** satisfy the relation:

$$2.33 \leq (T1+T2+G34)/T3 \leq 3.66.$$

13. The optical imaging lens system of claim **11** wherein a thickness of the second lens element along the optical axis is defined as T**2**, an air gap between the third lens element and the fourth lens element measured along the optical axis is defined as G**34**, a thickness of the fourth lens element along the optical axis is defined as T**4**, and T**1**, T**2**, G**34**, and T**4** satisfy the relation:

$$1.40 \leq (T1+T2+G34)/T4 \leq 2.56.$$

14. The optical imaging lens system of claim **11** wherein a sum of thicknesses of the first, second, third, and fourth lens elements is defined as ALT, and HFOV and ALT satisfy the relation:

$$3.22°/mm \leq HFOV/ALT \leq 12.49°/mm.$$

15. The optical imaging lens system of claim **11** wherein a thickness of the fourth lens element along the optical axis is defined as T**4**, and HFOV, T**1** and T**4** satisfy the relation:

$$5.33°/mm \leq HFOV/(T1+T4) \leq 21.30°/mm.$$

16. The optical imaging lens system of claim **11** wherein a sum of thicknesses of the first, second, third, and fourth lens elements is defined as ALT, a sum of air gaps between the first lens element through the fourth lens element along the optical axis is defined as AAG, and ALT and AAG satisfy the relation:

$$1.48 \leq ALT/AAG \leq 5.45.$$

17. The optical imaging lens system of claim **11** wherein a thickness of the fourth lens element along the optical axis is defined as T**4**, an air gap between the first lens element and the second lens element measured along the optical axis is defined as G**12**, and T**4** and G**12** satisfy the relation:

$$2.51 \leq T4/G12 \leq 27.50.$$

18. The optical imaging lens system of claim **11** wherein a sum of thicknesses of the first, second, third, and fourth lens elements along the optical axis is defined as ALT, and ALT and T**1** satisfy the relation:

$$2.92 \leq ALT/T1 \leq 4.14.$$

19. The optical imaging lens system of claim **11** wherein a thickness of the second lens element along the optical axis is defined as T**2**, an air gap between the first lens element and the second lens element measured along the optical axis is defined as G**12**, and T**2** and G**12** satisfy the relation:

$$8.00 \leq T2/G12 \leq 15.00.$$

20. The optical imaging lens system of claim **11** wherein a thickness of the second lens element along the optical axis is defined as T**2**, and T**1** and T**2** satisfy the relation:

$$0.86 \leq T1/T2 \leq 2.24.$$

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